

**MAKER-ORIENTED CURRICULUM FOR HUMAN-CENTERED  
DESIGN AND PROTOTYPING INSTRUCTION**

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# **MAKER-ORIENTED CURRICULUM FOR HUMAN-CENTERED DESIGN AND PROTOTYPING INSTRUCTION**

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## **LIST OF SYMBOLS AND ABBREVIATIONS**

CRT	Creative Technologies
CSOB	Campbell School of Business at Berry College
DBR	Design-Based Research
HBL	HackBerry Lab
HCI	Human-Computer Interaction
MUC	Mobile and Ubiquitous Computing
PBL	Project-Based Learning
PCL	Physical Computing Lab at Berry College
PD	Participatory Design
PrBL	Problem-Based Learning
DDE	Dual-Degree Engineering
MOLA	Maker-Oriented Learning Approach



## SUMMARY

Over the last ten years, the maker movement has increased the availability and access to tools and technologies that enable rapid prototyping to take place across a variety of disciplines. One discipline in which the demand for such tools and technologies is emerging is that of human-centered design and human-computer interaction in undergraduate and graduate computer science and engineering programs. Integrating these technologies into a curriculum through a maker-oriented learning approach, however, can pose significant challenges such as structuring rapid prototyping activities to meet the learning goals associated with these university programs, as well as overcoming the infrastructural issues associated with conducting hands-on activities in traditional classrooms. In this work, I will address these challenges by proposing a maker module framework through which maker-oriented activities can be developed that satisfy the curricular needs of human-centered design and human-computer interaction courses. Furthermore, I will present a summative curriculum of these maker modules and demonstrate the process through which they were developed and the role they play in a maker-oriented learning approach. Finally, I will detail a variety of practical implementation recommendations that enable these modules to be conducted in classroom environments. By doing so, this work will help to establish a foundational model that allows instructors to better structure maker-oriented activities in their course curriculum.

## **CHAPTER 1. INTRODUCTION**

As the role of human-centered design and human-computer interaction continues to expand its role in undergraduate and graduate computer science and engineering programs, the demand for tools and technologies to study these concepts continues to increase. Part of this demand includes providing students access to digital fabrication tools that assist them in producing physical prototypes to explore the human-centered concepts taught in these programs. While the maker movement has resulted in the proliferation of 3D printers, laser cutters, and easily programmed microcontrollers, there remains a need to formalize the implementation of these technologies into course curriculum. This work focuses on the development of a curriculum method that merges elements of human-computer interaction and computer science, with rapid physical prototyping. In doing so, this work lays out methods and techniques that have been developed through iterative design-based research.

Throughout this work, I will introduce the motivations and goals associated with maker-oriented learning in classrooms, as well as how these concepts were introduced to students during experimental sessions in computer science courses at Georgia Tech. From these sessions, this work will detail how a series of “maker modules” were developed that became the foundation of this work. Furthermore, I will show how this foundation evolved into a curriculum that is now being implemented as part of a degree program offered at Berry College. In doing so, I will demonstrate the impact such a curriculum can have, as well as the unique contribution this work makes to the growing study of human-centered design and human-centered computing.

This dissertation is presented in chapters that will answer three distinct research questions surrounding the development of this maker-oriented curriculum. These questions are as follow:

1. What are the elements that should be considered when developing a framework for maker modules in human-computer interaction courses?
2. What does a holistic curriculum of maker modules consist of?
3. What considerations and practices are necessary when implementing maker modules in a traditional classroom and curriculum?

Through answering these three research questions, there are four unique contributions that I make to the field of maker-oriented education. First, I introduce the concept of a maker-oriented learning approach as it applies to human-computer interaction (HCI) courses taught in colleges and universities. Second, I provide an actionable framework for educators to use when developing maker-oriented curricula to incorporate into those courses. Third, I provide a robust catalogue of maker modules that have been iteratively developed using this framework and have been implemented and tested in classrooms. Finally, I share a collection of criteria developed to assist in adapting the maker modules to fit the practical constraints of the classrooms in which they will be conducted.

The Chapter 2, *Background and Development*, will detail the existing literature that has provided a foundation for this work, as well as an overview of the curriculum that was piloted during four computer science courses taught at Georgia Tech and six creative

technologies courses taught at Berry College between 2015 and 2018. In Chapter 3, *Data Sources and Methods*, describes the data that was gathered from these courses and the methods used to analyze it. The next chapter, *Maker Module Framework Development*, will address the first research question (R1) regarding the individual elements developed to make a successful maker module. It will discuss the iterative design approach that was taken to develop it and the role it served as part of a formalized HCI curriculum. The following chapter, *Maker Module Curriculum Development*, will address the second research question (R2) which explains the process through which the holistic maker-oriented curriculum was developed. This will include a discussion of how specific modules were chosen and the impact that the order of the modules had on student learning and performance. The last chapter, *Practical Implementations for Maker Modules*, will answer the third research question (R3) and discuss the practical methods developed during this study through which physical prototyping activities can be integrated into university classrooms and curriculum.

## CHAPTER 2. BACKGROUND AND DEVELOPMENT

In order to understand the iterative and design-based research methods through which this work was developed, it is important to look at the underlying forces that are driving classroom-based, maker-oriented efforts. This includes examining the rise and influence of university-based makerspaces as well as narrowing the meaning of maker-oriented learning as it is used in this work. Furthermore, I will describe the method through which this curriculum was developed through concurrent in-class efforts at Georgia Tech and Berry College.

### 2.1 University Makerspaces and Maker-Oriented Learning

This work exists at the intersection of the technology resources of university-based makerspaces and the cross-disciplinary instruction of *human-centered design* (HCD) in undergraduate computer science courses. The interplay between these influences has given rise to the concept of *maker-oriented learning*, a concept that engages students in problem- and project-based learning through the use of digital fabrication tools popularized by the maker movement. In this section, I will explore the origins of university-based makerspaces and their influence on this work, as well as how trends in technology design courses common in human-computer interaction (HCI) programs have leveraged these spaces.

### *2.1.1 Emergence of University-based Makerspaces*

Throughout a university campus, it is possible to find a variety of places that could qualify as a makerspace. The concept of a makerspace grew out of three traditional spaces where creative work was accomplished: fab labs, hackerspaces, and co-working spaces [1]. A fab lab (short for fabrication lab) largely focuses on digital fabrication tools, such as 3D printers, CNC machines, and other tools that assist in the creation of physical artifacts [2-4]. Hackerspaces, on the other hand, focus on software-oriented activities such as traditional programming, mobile app development, and web development [5]. Co-working spaces are designed to accommodate collaborative work, facilitate visibility of work in progress, and stimulate meaningful interactions between people in the space [1]. In this work, I define a makerspace as a place that combines the elements of these three to establish an environment where creative work can be ideated, fabricated, and critiqued [6]. As such, the development of these spaces on a university campus has the potential to influence maker-oriented learning as they can provide a gathering point for maker activities both inside and outside of classes [7, 8]. Makerspaces have often times served as a site for learning to occur [9, 10]. This learning takes on a variety of forms including independent learning, discovery-based learning, collaborative learning, and formal learning [9-11].

Forest notes that while “creativity, invention, and innovation are values championed as central pillars of engineering education...university environments that foster open-ended design-build projects are uncommon” [7]. He goes on to contend that the development of university-based makerspaces can overcome this issue as the open

environment of these spaces lend themselves to discovery-based learning opportunities as participants in these spaces engage in independent project-based work [7].

Beyond independent learning, makerspaces oftentimes function as social and community-driven spaces where collaborative learning can take place [12]. Because these spaces function as co-working spaces for fabricators (participants that work with physical and tangible mediums) and hackers (participants that work with intangible mediums), collaborative learning often times occurs when projects leverage the knowledge resources and skill sets of multiple members within the space [12, 13]. As such, these spaces become a community of learners that engage in a practice of knowledge sharing. Finally, many spaces have embraced formal learning models through the offering of classes, workshops, and certifications [10]. This allows members to build competencies while increasing the overall availability of skills throughout the space, often through the development of a project-based goal [14].

Finally, understanding the physicality of a university makerspace can help demonstrate the role it can play in learning. A university makerspace represents a single physical location in which all functional aspects of a makerspace can be found, i.e. fab-lab, hackerspace, and co-working space. These spaces are often designed to serve the university population at large, including students and faculty in the development of academic work, and in some cases, personal projects [8]. As such, they are generally known across the campus as a resource in the same sense that students are aware of an athletics facility where they can go to exercise. They can be utilized for both specific classroom activities and out-of-class assignments [7]. The strengths of these spaces come from their ability to act as a one-stop shop for fabricating prototypes. For example, it is

not uncommon for a student to arrive at one of these spaces with just the requirements for a classroom assignment and leave with a basic prototype in hand [7]. That is because these spaces are able to help the student brainstorm ideas, design, fabricate, and program their prototype [7, 13].

### 2.1.2 *A Maker-Oriented Learning Approach*

As university-based makerspaces have grown on campuses, there has arisen a number of ways in which academic programs have begun to leverage these resources. This growing trend has given way to the development of a concept called the *maker-oriented learning approach* (MOLA). In this approach, elements of active, hands-on learning are joined with Problem-based Learning (PBL) and Project-based Learning. The structure of PBL as a scaffold for Project-based Learning outlined by Barron can serve as a framework for learning structures that can be provided with kits that scaffold workbench making [15]. In Learning by Design (LBD) many of these same ideas are put forth, but with a focus on a structured iterative process [16].

In PBL, learners are presented with a problem to solve. This problem should activate prior knowledge and allow for the learners to build upon this knowledge by working in small collaborative groups. The groups work together to construct a model to explain a problem then to test these models. As the learners test these models, they develop new understandings and uncover new questions. This triggers the same process, where learners try to understand the new problem by building and testing models [17]. Barron explored PBL in relationship to Problem-based Learning. In these structures PBL served as entry points to projects, scaffolding student learning so they understood how to



develop models, test, iterate and revisit a project within the constraints of a specific problem. In Problem-based Learning, students are introduced to projects that they are able to work on over a greater period of time than PBL [15]. This problem would be an open-ended real-world problem that involves a complex task that gives students the opportunity to collaboratively work toward an authentic end product or presentation [18]. A challenge with Problem-based Learning is that students can struggle without appropriate scaffolding and the advantage of first implementing PBL is that it provides students with experience in solving related open-ended projects.

In LBD a more structured approach to learning with design is outlined. This typically involves a sequence of activities that focus on an initial design challenge using only prior knowledge, a whole class discussion to share ideas, identifying additional knowledge needed to move forward to improve the design, and ongoing iterative steps to address issues that students need to learn to improve their design. This often involves a similar pedagogical process to a design studio course with students doing experimental work that is interspersed with informal pinups. During these pinups, students share ideas, reflect on the learning process, and then generate additional issues that can be addressed [19].

Given these elements of Problem- and Project-based Learning, combined with the capabilities afforded by university-based makerspaces, I will narrow the scope of maker-oriented learning as used in this work to the following characteristics:

1. Learning must be structured for a formalized educational setting
2. Engage students in hands-on work that results in interactive, tangible artifacts
3. Utilize digital fabrication tools popularized by the maker movement

4. Encourage visibility of work through a studio-style setting
5. Strive to be contextualized within human-centered experiences

#### 2.1.2.1 Learning Must Be Structured for a Formalized Educational Setting

The terms *maker* and *makerspace* have been used to describe a wide array of individuals and facilities where creative work takes place. For a maker-oriented learning approach, however, it is important to make a distinction about how the learning is structured. In this work, the scope is constrained to formalized educational settings, namely undergraduate and graduate-level courses that utilize maker principles and tools. This constraint is helpful in that it defines the opportunities and limitations that come with a generalized set of assumptions that can be made about these courses. These include, for example, the existence of an instructor, students, classroom space, timed class sessions, graded assignments, a syllabus with stated learning goals, etc. While there are certainly exceptions to these assumptions in some classrooms, this structure is important to consider when developing a formalized curriculum so that it can address the demands that most courses would require. While it is possible that this work could be used in other settings, such as self-guided learning or an informal learning community like community-based makerspaces, there are dynamics specific to those groups that I will not address.

### 2.1.2.2 Engage Students in Hands-On Work that Results in Interactive, Tangible Artifacts

Engaging students in hands-on work is an important requirement for maker-oriented learning not only because it is essential for creating physical artifacts, but because it allows students to develop a deeper understanding of their work. This tactile approach has been shown to be effective in conveying science and engineering skills to students with various capabilities [20]. Both Kolko and Lindtner showed that DIY maker activities were useful in teaching science and engineering skills because of the interdisciplinary and hands-on nature of the approach [20, 21]. Because of the engagement and motivation surrounding maker-oriented approaches, Honey demonstrated that it is possible to improve meta-cognition and build relevance to core STEM principles through making and tinkering in classroom environments [11]. This hands-on approach leverages the benefits of Piaget's Constructivism that asserts that knowledge can be effectively established when "students build, make, and publicly share objects" [22].

The tangibility of the artifacts created also creates additional unique learning opportunities. By enabling physical manipulation of the work, creativity and participation can be increased by offering novel ways for students to experience their work [23]. Furthermore, the visibility of work contributes to a student's ability to understand their progress through the design cycle because the artifact has a permanent, physical presence [24]. This approach distinguishes itself from maker-oriented approaches that largely emphasize software development where the visibility of progress can sometimes be more obscure [25]. For example, a student developing an interactive lamp will have various

physical drawings, paper models, 3D prints, and hardware that are constantly visible and present for both students and instructors to evaluate.

Because learning is situated within human-computer interaction courses, another characteristic of the final work is that it should be interactive. In this use, interactivity is coarsely defined to allow for a variety of artifacts, both electronic and non-electronic. It relies upon a model of interactivity that uses the transfer of information from inputs to processing, and processing to outputs [26]. In electronic devices, this interactivity can be achieved through the use of electronic transducers (sensors) that turn one form of energy, such as light, heat, or movement, into an electrical signal that can be processed. This processing then uses a programmed algorithm to determine an appropriate action resulting in an output from the system's actuators such as motors, lights, or speakers. Non-electronic interactive artifacts can seem elusive when compared to the sophisticated possibilities available with modern electronics. However, from a human-centered design perspective, such artifacts are just as valuable. In these artifacts, the inputs, processing, and outputs are almost exclusively generated through mechanical means.

Examples of this model of interactivity can be understood through a few examples (Figure 1). A simple nightlight exhibits the principles of an electronic interactive device very well. It uses a light sensor to measure the amount of light in a room. The signal is processed by a simple circuit that uses a threshold to determine when the room is either dark enough to turn on the lamp, or light enough to turn off the lamp. This signal then triggers the appropriate action for the lamp's bulb. Destin Sandlin's "Backward Bicycle," however, is a novel example of a non-electronic interactive device [27]. The concept of the bicycle is that its steering mechanism is reversed such that turning the handlebars left

results in the front wheel turning right and vice versa. In this system, the handlebars operate as the inputs, receiving mechanical input from the user. The gear mechanism that reverses the direction of the steering acts as the processing unit in the system and uses a simple algorithm of transforming left to right and right to left. The output of the system is the resulting direction of the front tire. As such, even with non-electronic devices, unique and novel interactions can be developed.



*Figure 1 – Examples of electronic and non-electronic interactive devices include a simple nightlight and a reverse-steering bicycle.*

#### 2.1.2.3 Utilize Digital Fabrication Tools Popularized by the Maker Movement

Another way in which I will distinguish the maker-oriented learning approach is that the artifacts created through this method should leverage digital fabrication tools that are common among makerspaces. In the last ten years, many of these tools have become widely available to the public, in part because of their popularization through the maker movement [28]. This includes tools such as 3D printers, CNC routers, laser cutters, and

Arduino microcontrollers. The proliferation of these tools has resulted in large communities of support and many efforts to create educational material utilizing their capabilities [29-31]. The benefits of such tools derive from advantages such as cost of operation, inexpensive materials, speed of fabrication, resource sharing, and connections to discipline-specific topics.

The cost of operating these digital fabrication tools has experienced a sharp decline over the last several years. 3D printers for example, were historically industry-specific machines due to the complexity of operation and immense cost with many printers costing \$500,000 or more [32]. However, early maker communities, such as the RepRap project, developed low-cost alternatives that have brought the cost of prototyping-quality printers down to between \$300 and \$2,000, making them more suitable for students and hobbyists [32, 33]. Similarly, the cost of materials for printers have significantly dropped from \$10 per kilogram to under \$2 per kilogram from 2008 to 2018 [32]. Similar cost efficiencies have been observed across various digital fabrication tools with the emergence of hobby-grade tools for maker communities. This drop in cost has resulted in a proliferation of these technologies by educational institutions and have allowed for their inclusion in traditional classrooms where it was previously financially infeasible to do so [34]. Furthermore, the speed at which these tools are capable of creating complex designs presents an advantage for students to rapidly iterate on designs. This iterative process helps develop a deeper understanding of the work and promotes problem-solving in the design process [35]. From a practical standpoint, it also allows students to complete iterative work in the timeframe of a single semester, making it easier for instructors to constrain projects to a single course.

In addition to the operational advantages of these tools, there are opportunities to enhance classroom learning with them as well. The digital nature of these tools allows for students to share their work and engage in participatory learning as they interact with each other in groups and with their instructor [34]. This sharing results in students not only being able to offer feedback and contribute to their peers' work, but also provides opportunities for students to reflect more deeply on their own work and how their approach compares to others in the course. The ability to benefit from shared work extends to resources outside of the classroom as well. As repositories such as Thingiverse, Instructables, and OpenProcessing, continue to curate digital designs that can be downloaded, remixed, and fabricated, students will be able to build upon a wide body of creative work [36].

Finally, these digital-fabrication tools share a strong connection to discipline-specific topics such as computation, human-centered design, and fabrication, making them an advantageous extension of traditional topics taught in computer science and engineering courses. For example, introducing elements of physical computing with an Arduino has shown to help enhance computer programming courses by providing students with a tangible way of visualizing abstract concepts of computation [37, 38]. Thus, it is possible to present students with opportunities to connect curriculum-specific topics to work that can be developed through these digital fabrication tools.

#### 2.1.2.4 Encourage Visibility of Work Through a Studio-Style Setting

Implementing maker-oriented curriculum into traditional classrooms can pose a variety of practical challenges. These include adopting spaces to better facilitate showing

student work and engaging students in providing feedback and critique on each other's work [39]. To overcome these challenges, adopting certain elements from traditional design studio settings can often times be appropriate. Many of the requirements of design studios mesh well with the learning goals of a maker-oriented curriculum. Vyas proposed that the requirements of a design studio space should include the following: deal with open-ended problems, carry out rapid design iterations, use heterogeneous media, support formal and informal critiques, and making creative use of constraints [24]. The ability to deal with open-ended problems is fundamental to the maker-oriented approach as discussed previously. The ability to accommodate rapid design iterations is enabled through digital fabrication tools such as 3D printers, allowing students to quickly prototype, test, and evaluate their designs [22]. Furthermore, the variety of materials and methods supported by these digital fabrication tools gives way to heterogeneous media that affords students the flexibility in determining an approach to solving technology-focused problems [34]. Because such an approach can result in students taking different approaches than their peers, it becomes increasingly important to support critique such that students are able to not only share insights gained through their own design process, but also to give them an opportunity to reflect on other students' work. Finally, design studios should allow students to make creative use of constraints. This element is well rooted in maker culture, particularly with regard to repurposing, hacking, or upcycling existing artifacts to serve some new creative purpose [40].

Many of these criteria are implementable in traditional classrooms with relatively few physical changes to the space. Access to electrical outlets, moveable tables and chairs, and access to presentation technology are among some of the easiest changes to



implement that can begin to encourage a design-studio mindset in a course. Vyas further expands on this concept through the description of “artful surfaces,” e.g. surfaces that designers use to make the less tangible parts of their design process visible [24]. These can be dry erase boards, cork boards, or tables where sketches, paper prototypes, and post-it notes can be organized. Such surfaces allow both instructor and students to better understand a project’s design process and oftentimes can help pinpoint where a wrong decision has been made.

#### 2.1.2.5 Strive to Be Contextualized Within Human-Centered Experiences

The last criteria for maker-oriented learning is that the curriculum and design challenges should be designed to allow students to contextualize the concepts as they relate to human-centered experiences in the world. This constraint allows the maker-oriented approach to be relevant to the HCI-focused courses in which it will be used, as well as an effective method for assisting students in understanding the larger real-world context in which these concepts can be implemented [41]. As such, this understanding can oftentimes provide motivation for students to transfer learning to other disciplines as they develop personal connections with the material. This includes allowing students to personalize the topics of their design-based projects. For example, a design challenge centered on senior health technology, may encourage students to identify design issues affecting close relatives. Such approaches increase student satisfaction and can promote transfer between courses [11, 22, 42].

## **2.2 Curriculum Development at Georgia Tech and Berry College**

Between August 2015 and June 2018, I iteratively developed maker-oriented curricula in courses being offered at Georgia Tech and Berry College. While each institution has unique motives for implementing maker-oriented curricula, the insights and results gathered from both institutions have largely inspired and affected the other. The approach taken in the development of the curriculum has largely been through the lens of design-based research.

Design-based research (DBR) is a fundamental tool for exploring and developing new concepts in the learning sciences [43]. This research method involves developing solutions to problems, known as interventions, and testing them in situ to evaluate their effectiveness. Often times the results of these evaluations lead to further iteration and development of these solutions and examining improvements within that process. While this process can be susceptible to uncontrolled variables given the naturalistic setting in which the testing takes place (such as a classroom), Barab argues that DBR is a valid approach for contributing to existing theories or even developing new theories [43]. Furthermore, it has been shown to be an effective tool in developing new artifacts and practices within the learning sciences community [43, 44]. In this work, DBR was used to develop a collection of artifacts that will influence and assist instructors implementing maker-oriented principles into their formalized curriculum.

### *2.2.1 Iterative Development at Georgia Tech*

The core development of this work took place within four courses offered between 2015 and 2016 at Georgia Tech. During these years, I developed interventions that were

principally deployed during four courses (CS 3750 and CS 4605), and as supplemental material in one course (CS 6452).

*Table 1 – Georgia Tech courses that utilized maker-oriented interventions in their curriculum.*

<b>Course #</b>	<b>Course Name</b>	<b>Semester/Year</b>	<b>Class Size</b>	<b>Students</b>
CS 4605	Mobile and Ubiquitous Computing	Spring 2015	32	Undergrad, Grad
CS 3750	User-Interface Design	Fall 2015	68	Undergrad, Grad
CS 6452	Prototyping Interactive Systems	Fall 2016	24	Grad
CS 4605	Mobile and Ubiquitous Computing	Spring 2016	38	Undergrad, Grad
CS 3750	User-Interface Design	Fall 2016	69	Undergrad, Grad

The four courses through which the interventions were principally implemented consisted of two separate offerings of User-Interface Design (CS 3750) and Mobile and Ubiquitous Computing (CS 4605). In the CS 3750 course, the principles of human-computer interfaces are introduced and is meant to focus on the capabilities of both humans and computers through the lens of interoperability and usability. The CS 4605 course, however, explored the foundations of mobile devices and ubiquitous technology. It presented these topics through ongoing research in the field as well as through experimentation with technologies. A significant goal for each of these courses was to have students explore the topics of the course through the development of a human-centered technology. One of the challenges associated with this goal was accommodating the variety of prior knowledge and experiences of the students because of the wide variety of majors that made up each class (Table 2).

*Table 2 – Breakdown of majors in Georgia Tech maker-oriented courses.*

<b>Major</b>	<b>CS 3750 - F2015</b>	<b>CS 4605 - S2016</b>	<b>CS 3750 - F2016</b>	<b>CS 4605 - S2017</b>	<b>Total</b>
Architecture	1	1	-	-	2
Business Administration	-	-	1	-	1
Biomedical Engineering	2	-	-	1	3
Chemical Engineering	-	1	-	-	1
Chemical and Biomedical Engineering	1	-	-	-	1
Computational Media	5	8	6	4	23
Computer Engineering	-	-	2	-	2
Computer Science	37	26	33	26	122
Electrical Engineering	1	1	-	-	2
Industrial Engineering	20	-	25	-	45
Mechanical Engineering	1	-	-	1	5
Psychology	-	-	1	-	1
Special Topics	-	-	2	-	2

One way to address this variety of students is through a cross-disciplinary approach that would allow students to work together in groups to create prototypes that exhibit evidence of the concepts learned in the class [1, 11, 45]. Because this prototyping process would be new for many students, I developed a series of “maker modules” that would introduce students to design principles and fabrication skills that would help the students in the production of these technology prototypes. These modules served as a scaffold for engaging students in problem-based design challenges that would transfer into the open-ended projects they were assigned as part of the course curriculum. In open-ended projects, it is often necessary to provide a set of tools and reference points to help students achieve the desired learning outcomes [15, 42]. Furthermore, the artifacts created during these maker modules would serve as a scaffold for cognition, inasmuch that students would be able to extrapolate on the brief design process used during the modules and apply it toward the longer, more complex process for their large projects [46].

#### 2.2.1.1 Maker Modules

The development of the maker modules focused on three criteria. First, the modules must complement the themes and topics being discussed in the courses in which they are used. Second, the modules should introduce students to skills and technologies that can be used in the production of a problem- or project-based assignment for the course – usually a semester-long project. Third, the modules should be implementable in a wide variety of classroom types and focus on accessible tools and materials.

In order to complement the themes and topics in the course, I began coordinating and planning with instructors several months prior to the start of the course. During these sessions we discussed the curriculum, syllabus, desired learning outcomes, and projects that were to be implemented in the course. Through this process of requirements gathering, we were able to touch on several themes which we could implement in the modules. These included elements of understanding the current state of technology and its underlying functions, limitations and constraints of technology systems, and principles of basic interaction between humans and technology. Through this, we decided that each module should contain a design challenge that constrains students to a specific domain to help focus their thinking on a defined set of circumstances and requirements for their designs.

The second criterion considered was to help students become comfortable with tools and technologies that enable them to rapidly fabricate prototypes. It was determined that many students would come into the class with a very limited understanding of digital fabrication tools, and that personal experience with such tools would be absent or limited prior to the course. Furthermore, the modules were structured in a way such that skills

and knowledge gained in one module could be used in later modules. This approach would allow students to continue developing skills and scaffold the introduction of new skills along the way. This approach was the result of iterative design as each semester brought additional insights into the order in which modules should be taught, as discussed in the *Maker Module Curriculum Development* chapter.

Introducing students to these tools and technologies was done through both in-class and out-of-class interventions. Students were given an introduction to the technologies through in-class exercises with the goal of producing a simple artifact that displayed a basic level of proficiency with the tool. This simple artifact was usually tightly constrained across all the students to allow them to compare and contrast their results with their peers. Where appropriate, the modules are then designed to provide students with an out-of-class activity that gives them an opportunity to connect the theoretical concepts taught in the class to the fabrication skills learned using the technology during the module.

The last criterion focuses on the practicality of implementing such activities in a classroom on a university campus. It was understood that the size of classes would range from as few as 20 students to over 70 in some cases. This presented a significant challenge with regard to adapting traditional learning classrooms into spaces that can support collaborative, creative work, as well as how to organize and distribute physical materials and tools to students. From this effort, I developed a number of guidelines that contrasted providing resources to students through a kit-based model (individualized collections of tools and materials) versus a workbench model (centrally located tools and materials organized by type) (Figure 2). The process by which these

determinations was made was also highly iterative, with modifications being made between individual activities and throughout course offerings. As I have refined that process, recommendations are made for each activity specific to the technology being used, as well as the classroom space and number of students. These findings will be discussed in the *Practical Implementations for Maker Modules* chapter.



*Figure 2 – Comparison of a traditional kit (left) and a workbench kit (right). Each has similar components but are assembled and presented differently to students based on the desired learning outcomes of an activity.*

In total, I developed six distinct maker modules during this development period at Georgia Tech. They include rapid foam board prototyping, 2D design and fabrication, 3D design and fabrication, wearable technology prototyping, interactive prototyping with Arduino, and deconstruction of technology.

#### 2.2.1.2 Maker Module 1: Rapid Foam Board Prototyping

In Rapid Foam Board Prototyping students learn the principles of creating proof of concept models that are able to communicate basic design thoughts. This includes the ability to create low-resolution prototypes in a brief amount of time using inexpensive foam board and basic fabrication techniques.

*Criterion 1: Supporting Course Themes* – Throughout this process students are challenged to think about a simplified model of interactivity that defines the relationships between humans and devices. Their artifacts must follow this model and exhibit its features.

*Criterion 2: Promote Fabrication Technology Skills* – This module starts with basic tools of production such as hot glue guns, X-Acto knives, rulers, and foam board. These basic tools allow students to rapidly explore developing physical paper prototypes through activities with a low barrier of entry and shallow learning curve.

*Criterion 3: Practical Classroom Considerations* – This module is highly implementable across a variety of classroom setups and sizes. For this module, work is done in groups and students are provided with resource kits that include the tools and materials necessary to complete the design challenge.

#### 2.2.1.3 Maker Module 2: 2D Design and Fabrication

After rapid paper prototyping, students are exposed to automated forms of prototyping using basic CNC digital fabrication tools such as laser cutters and vinyl cutters. They explore vector-based design software for creating compatible designs and produce prototypes that are limited by physical and aesthetic constraints.

*Criterion 1: Supporting Course Themes* – In this module, students explore the relationship between form and function as well as the role of precision in the development of interfaces.

*Criterion 2: Promote Fabrication Technology Skills* – Students are introduced to vector-based design software, as well as the principles of subtractive CNC fabrication



tools. They learn basic safety and operation of these tools and are given a design challenge that solidifies those principles.

*Criterion 3: Practical Classroom Considerations* – This module is split between an in-class and out-of-class activity. The in-class activity focuses on each student developing a vector-based design that is capable of being laser cut or vinyl cut. Students then observe the CNC tools in operation through a recorded or live demonstration. Out-of-class, students use the laser cutter and vinyl cutter to fabricate their design. This approach is structured to accommodate the limited quantity and availability of the CNC tools.

#### 2.2.1.4 Maker Module 3: 3D Printing and Design

In 3D printing and design, students are challenged to consider how the fabrication of more complex geometries can improve their designs and promote interactivity.

*Criterion 1: Supporting Course Themes* – By engaging in more complex physical designs, students are able to explore and implement ergonomic considerations into their designs. Because of the rapid prototyping capabilities of 3D printers, they also explore the importance of iteration and evaluation of their designs.

*Criterion 2: Promote Fabrication Technology Skills* – In this module students engage with both 3D design software programs and 3D printers. Students practice 3D design principles by creating designs based on specific design constraints and fabricate simple objects on the 3D printer and learn basic maintenance and operations of the printers.

*Criterion 3: Practical Classroom Considerations* – This module usually spans two class session because of the broad scope of the material and technology. In the first

session, students explore the sources of 3D designs (online repositories, 3D scanning, or custom design in 3D software) and focus on designing their concepts in software. In the second session, they engage with the 3D printers and work on basic operations and printing a sample object. Because of the time required for 3D printing, students print their custom objects outside of class. This allows for iteration and troubleshooting to take place on the students' own time.

#### 2.2.1.5 Maker Module 4: Wearable Technology Prototyping

In wearable technology prototyping, students expand on many of the skills learned in previous modules through the lens of creating a wearable technology device.

*Criterion 1: Supporting Course Themes* – Wearable technology brings the development of human-interfaces directly onto the user's body. As such, students learn the constraints, limitations, and opportunities associated with the development of such devices. They also explore five design factors that dictate wearable design constraints including device location, weight, size, comfort, and movement.

*Criterion 2: Promote Fabrication Technology Skills* – This module expands on the previous three modules and introduces additional rapid-prototyping materials and techniques that are specific to wearable design. This includes soft-goods materials such as fabric and Velcro, as well as moldable thermoplastics such as Instamorph or Shapelock that allow students to create ergonomic and form-fitting devices.

*Criterion 3: Practical Classroom Considerations* – Like the rapid paper prototyping module, this module is also highly implementable across a variety of classroom setups and sizes. The tools and materials in this module, however, are distributed using a

workbench-style setup that allows students to diversify their designs through the variety of materials provided to them.

#### 2.2.1.6 Maker Module 5: Interactive Prototyping with Arduino

In this module, students are able to explore the relationship between software and hardware development through the Arduino microcontroller. This allows them to introduce electronic interactivity into their previously designed prototypes.

*Criterion 1: Supporting Course Themes* – This module deepens the students understanding of the model of interactivity introduced in the first maker module, and ties directly into themes of human-centered devices and interfaces.

*Criterion 2: Promote Fabrication Technology Skills* – Students work through this module creating interactive circuits that expand on their programming skills through the Arduino interactive development environment. They fabricate simple circuits that interact with humans and the environment and work through design challenges that allow them to develop strong relationships between software and hardware.

*Criterion 3: Practical Classroom Considerations* – This module scales well across a variety of classrooms and allows students to work individually or in small groups depending on the previous software and hardware experience of the students. The Arduino devices are small, inexpensive, and compatible with a variety of operating systems, resulting in very few technical challenges during the module.

#### 2.2.1.7 Maker Module 6: Deconstruction of Technology

The deconstruction of technology module is geared toward promoting technology design awareness among students. It further encourages students to explore and experiment with technology to determine its function and the choices made by designers and engineers during the development and production of these devices.

*Criterion 1: Supporting Course Themes* – Open-ended exploration and critical thinking about technology design is core to many of the courses in which these modules are used. As such, allowing students to deconstruct common human-interface devices such as keyboards, mice, and game controllers, allow them to understand and explore how these devices function in the real world.

*Criterion 2: Promote Fabrication Technology Skills* – Through the deconstruction (and subsequent reconstruction) of these devices, students interact with hand tools and the technologies within the devices to determine their functionality.

*Criterion 3: Practical Classroom Considerations* – This module scales well and requires very few additional resources in order to implement it in medium or large classrooms. The tools and materials for this module are commonly available within the organization's IT department, making it less resource-intensive than some of the other modules.

#### 2.2.2 *Curriculum Refinement at Berry College*

As progress commenced for the Fall 2015 offering of CS 3750 User Interface Design at Georgia Tech, a concurrent effort was being made to develop a course at Berry College that concentrated on hands-on prototyping practices and design principles through a maker-oriented approach. The course, CRT 101 Introduction to Prototyping,

was introduced as a course for the newly created Creative Technologies program at Berry and was intended to give freshman and sophomore students a foundational understanding of creative design thinking through rapid prototyping. Iterative development of this course took place in six course offerings through Spring 2018. The curriculum developed during these iterations has expanded upon the principles developed during the interventions at Georgia Tech.

#### 2.2.2.1 Background of Creative Technologies at Berry College

As a relatively new discipline, it is important to understand the background of the *Creative Technologies* (CRT) program at Berry College to see how a maker-oriented curriculum and the Introduction to Prototyping course plays a role in contributing to the program's learning goals.

In response to a directive to explore developing an engineering program at the college, Berry introduced a new Bachelor of Science degree in Creative Technologies. This program was intended to be an interdisciplinary liberal-arts approach to addressing elements of engineering, computer science, design, and entrepreneurship. The goal of the program is to prepare students for careers in a variety of technology-based disciplines such as rapid prototyping, hardware and software development, product design, and educational technology. It achieves this through the use of “hands-on technology projects as the means for developing student creativity, analytical and problem solving skills, mathematical and scientific reasoning, collaborative abilities, aesthetic sensibilities, computing, programming skills, project management skills and strategic insights” [47]. The requirement for students to develop hands-on technology projects relies on a variety

of maker-oriented disciplines including 3D printing, programming, laser cutting, circuit design, computer-aided design, CNC machining, robotics, rapid prototyping, welding, and woodworking.

The program itself contains a variety of courses that allow students to develop a broad spectrum of skills across technology fields, as well as a selection of elective courses that serve to personalize the student's field of study. As of Fall 2018, the current program of study includes 30 hours of required coursework and 6 hours of elective courses (Table 3, Table 4). These courses pull from a variety of departments at Berry including computer science, physics, marketing, management, and creative technologies.

*Table 3 – Required courses Creative Technologies major at Berry College [48].*

<b>Course No.</b>	<b>Course Name</b>	<b>Credit Hours (Class-Lab-Total)</b>
CRT 100	Introduction to Creative Technologies	1-0-1
CRT 101	Introduction to Prototyping	2-2-3
CSC 103	Creative Computing	3-0-3
CSC 235	Physical Computing	2-2-3
PHY 240	Practical Electronics	2-2-3
CRT 300	Rapid and Improvisational Prototyping	0-2-1
CRT 310	Innovation and Commercialization	3-0-3
CRT 320	Programmable Logic Controllers and Robotics	2-2-3
ENT 340	Introduction to Entrepreneurship	3-0-3
CRT 399	Intermediate Design Studio	2-2-3
CRT 450	Senior Professional Development Seminar	1-0-1
CRT 499	Senior Design Capstone	3-0-3

*Table 4 – Elective courses Creative Technologies major at Berry College [48].*

<b>Course No.</b>	<b>Course Name</b>	<b>Credit Hours (Class-Lab-Total)</b>
CRT 420	Special Topics	3-0-3 or 2-2-3
THE 404	Advanced Production	3-0-3
MKT 327	Qualitative Research Methods	3-0-3
PSY 350	Industrial and Organizational Psychology	3-0-3
PHY 321	Computational Methods in Physics	4-0-4
MGT 440	Advanced Entrepreneurship	3-0-3
---	Any 300-400 level CSC course	---
ART 327	Web Design	3-0-3
ART 340	Graphic Design	2-2-3
ART 351	Digital Imaging	2-2-3
COM 405	Applied Graphic Design	2-2-3
CRT 496	Technology Internship	3-9 Credits
CRT 498	Directed Study	3-0-3
CRT 300	Rapid and Improvisational Prototyping	0-2-1
CSC 120	Designing Programs: Problem-Solving	3-2-4
CSC 245	Web Technologies and Programming	2-2-3

Over the last eight semesters, the program has experienced significant growth compared to the computer science and dual-degree engineering programs at Berry College. There have been a number of factors influencing this including the transition of computer science as a standalone major to a concentration within the mathematics major and requirement changes within the dual-degree engineering program. One growing trend is students changing majors from computer science and dual-degree engineering to creative technologies.

*Table 5 – Comparative number of majors across dual-degree engineering, computer science, and creative technologies at Berry College (Fall 2013 – Spring 2018). Shaded area denotes semester that creative technologies program began [49].*

<b>Semester/Year</b>	<b>Computer Science</b>	<b>Dual-Degree Engineering</b>	<b>Creative Technologies</b>
Fall 2013	5	78	0
Spring 2014	5	59	0
Fall 2014	3	82	2
Spring 2015	4	61	13
Fall 2015	4	92	25
Spring 2016	6	80	29
Fall 2016	6	81	37
Spring 2017	6	59	48
Fall 2017	4	79	51
Spring 2018	11	53	68

As the CRT program has grown, both through its curriculum and student body, it became necessary to adapt and develop curriculum that would be appropriate for growing class sizes and would complement computer science and engineering topics and courses. It is these requirements that spurred development of an introductory course for creative technologies students.

#### 2.2.2.2 Role of Introduction to Prototyping in Creative Technologies

Prior to the introduction of the CRT major in fall 2014 and the first offering of CRT 101 Introduction to Prototyping in fall 2015, a few select courses were offered that served as a topical resource for the curriculum developed for CRT 101. These courses included BUS 358 Innovations, Design, and Prototyping, CSC 235 Physical Computing, and MGT 340 Introduction to Entrepreneurship. Through these three courses, several topics



emerged that helped define the maker-oriented focus utilized in the CRT 101 course and the curriculum that was developed for it.

BUS 358 contributed a variety of themes including problem-based projects, design thinking, and maker-inspired production using 3D printers and laser cutters, for example. During the fall 2014 and spring 2015 offerings of the course, the instructor partnered with a community makerspace near the college to offer increased access to technologies for students to use with their projects. This course also introduced the idea of including traditional fabrication techniques into the curriculum as well. Through the inclusion of woodworking and metal working, students were able to significantly expand both the scope and scale of their projects. As such, during the formation of the CRT 101 course, an additional maker module was developed to introduce these skills to students. With the introduction of the creative technologies program, this course was phased out and replaced with the CRT 101 course.

CSC 235 Physical Computing was also instrumental in contributing significant content and practices adopted in CRT 101. This course largely focuses on introducing students to electronics and programmable microcontrollers, such as the Arduino. It also introduces students to a fundamental model of interactivity and guides students through the process of creating multi-modal interactive electronics using sensors, displays, and actuators. Much of the introductory material in this course was included in two of the maker modules developed in conjunction with Georgia Tech. These modules included the foam board techniques used in the rapid paper prototyping module (used to create simple enclosures for electronics projects) and the introduction to interactive prototyping with Arduino. This class is now a required course in the CRT program, with most students

having taken CRT 101 prior to it. This effectively provides an additional touchpoint for students entering that course with additional familiarity with the interactive electronics topics taught. This course also inspired the creation of the last make module, which covers circuit design and soldering skills.

Finally, MGT 340 (now ENT 340) Introduction to Entrepreneurship helped shape the CRT 101 course in that the motivation for creating projects in the class should be human-centered. This is in response to the entrepreneurship course focusing on students developing small businesses that sell and market products to their peers and community. As another course that students take after CRT 101, it was decided that it would be beneficial to introduce students to human-centered design concepts that allow them to develop prototypes driven toward a user-based need.

Using these courses as a guide, the CRT 101 course was first offered in fall 2015. It has subsequently been taught every semester to date, resulting in six total classes. The course continues to be iterated upon using similar methods through which the maker modules were developed at Georgia Tech. The course is designed to accommodate 24 students, which fit both the physical constraints of the classroom space, and seemed reasonable given the practical implementation strategies developed while administering the modules to larger class sizes at Georgia Tech.

*Table 6 – CRT 101 classes offered and breakdown of student Creative Technologies majors and non-majors enrolled in the course.*

<b>Semester/Year</b>	<b>Class Size</b>	<b>Majors</b>	<b>Non-Majors</b>	<b>% Majors</b>
Fall 2015	17	6	11	35%
Spring 2016	19	7	12	37%
Fall 2016	23	10	13	43%
Spring 2017	22	12	10	54%
Fall 2017	20	11	9	55%
Spring 2018	25	17	8	68%

Because the number of students enrolled in the major has not yet reached maximum capacity, it was decided to allow non-CRT majors to enroll in the course as well. As the number of CRT majors has grown, the ratio of majors to non-majors has grown (Table 6). One unplanned result of incorporating non-majors into the course was students adding the CRT major upon completion of the CRT 101 course.

#### 2.2.2.3 Curriculum Development in CRT 101 Introduction to Prototyping

The structure of CRT 101 Introduction to Prototyping is based on students developing human-centered design skills through building hands-on projects with digital fabrication tools. The course approaches technology education through a broad approach to giving students a breadth of experience with maker-oriented tools and technologies, while allowing them to engage in problem-based learning through the production of prototypes.

The course meets twice a week, with two-hour class sessions, where students engage in learning the principles of human-centered design during guided lectures in the first meeting of the week and a problem-based design challenge during the second

meeting of the week. In total, the class meets 28 times in a semester, with most of the classes consisting of theory lectures and discussions or maker module labs (Table 7). The remaining sessions are dedicated to students pitching, preparing, or presenting work on projects, guest lectures, or the end-of-semester Prototyping Open House where students open their work to critique by the public and campus community.

*Table 7 – Class meeting breakdown of a typical CRT 101 course.*

<b>Session Type</b>	<b>Class Sessions</b>
Design Theory Lectures & Discussions	10
Maker Modules	8
Additional Labs	2
Project Preparation and Presentations	6
Guest Lectures	1
Prototyping Open House	1
<b>Total Sessions</b>	<b>28</b>

In the absence of an accompanying curriculum, as was the case with the User-Interface Design and Mobile and Ubiquitous Computing courses, a new curriculum was developed to address the needs of the human-centered design skills required by the CRT program. To address this, ten design theory lectures and class discussions were created. These discussions touch on topics such as affordances, signifiers, interactivity, design thinking, human cognition, and constraints. To supplement the lectures, the students read *The Design of Everyday Things* by Don Norman. This text provides students with additional context in which to understand the concepts through Norman’s ability to relate design concepts to familiar everyday objects and technologies [26]. Upon reading each chapter, students submit a reading reflection where they relate the concepts in the chapter to a personal experience they have had with technology. The reflection is due at the

beginning of the lecture where the concept will be discussed, allowing for students to contribute personal experiences during the discussion portion of the class.

Much like the courses at Georgia Tech, the CRT 101 course relies on problem-based projects to allow students to openly explore the design concepts learned during the lectures and discussions. Because this course is directed toward a less experienced student body – most students are freshman and sophomores, versus the juniors and seniors in the Georgia Tech courses – I structured the projects to be more tightly constrained take place over shorter periods of time. This is done to keep projects narrowly scoped as students adopt new knowledge, skills, and technologies into their repertoire. Thus, students are assigned two smaller projects, an intermediate project and final project, in which they implement the concepts learned in the class. Students have roughly six weeks for the intermediate project and seven weeks for the final project, during which they are to identify a personally compelling problem that can be addressed through the development of a new technology. For the purpose of this course, problems are broadly defined as systems that have some barrier or inefficiency. This broad definition allows students to choose projects that are personally-motivating. It also gives them flexibility when deciding the best methods, materials, and technologies in the lab to use in the production of their prototype.

The course also makes heavy use of the practical classroom considerations learned during the development of the maker modules at Georgia Tech. The ability to move tables and chairs, as well as the abundance of artful surfaces such as dry erase boards has been implemented into the course and used during both class discussions and maker modules.

#### 2.2.2.4 Maker Module 7: Traditional Materials – Wood and Metal

This maker module was inspired by the traditional materials and methods using during the BUS 358 course. It allows students to expand the scope and scale of their projects by using wood and metal as structural components for their designs.

*Criterion 1: Supporting Course Themes* – Working with wood and metal allow students to gain an appreciation for traditional fabrication methods and diversification of prototyping approaches.

*Criterion 2: Promote Fabrication Technology Skills* – Students learn to operate common woodworking tools such as miter saws, drill presses, band saws, speed squares, nail guns, and corner clamps. They also learn basic operation of MIG welders and angle grinders.

*Criterion 3: Practical Classroom Considerations* – This is one of the most difficult modules to implement and relies heavily on the availability of woodworking and metal working tools. In its current iteration, students cycle through the wood shop and are able to progress through the space because the design challenge steps procedurally through each tool. Welding, however, must be completed as an out-of-class exercise because of the limited availability of tools and safety equipment. Students schedule a 20-minute one-on-one session with the instructor or lab assistant to complete this assignment.

#### 2.2.2.5 Maker Module 8: Circuit Design and Soldering

In this module, students expand on the practical experience gained from the Arduino module to begin creating their own custom circuits, designing printed circuit boards, and soldering through-hole components.

*Criterion 1: Supporting Course Themes* – Designing circuit boards allows students to create interactive electronics that occupy a smaller footprint. Thus, they are able to more accurately test their designs and work toward commercially implementable designs.

*Criterion 2: Promote Fabrication Technology Skills* – Students advance their skills with circuit design software that uses breadboard representations, electronic schematics, and printed circuit board routing tools to create functional circuits. They also become proficient with soldering stations and learn practical methods for soldering through-hole components into a printed circuit board.

*Criterion 3: Practical Classroom Considerations* – Because this module builds off of the Interactive Prototyping with Arduino module, students are able to successfully adopt the circuit models and software needed to design circuit boards. One limitation of this module however is the turn-around time of getting circuit boards manufactured if students want to produce their designs. Current manufacturing lead times are around 5 to 7 days and may not scale well for a project that is to be completed by the following week.

## **CHAPTER 3. DATA SOURCES AND METHODS**

In order to facilitate the development of the maker module framework, the topics and order of maker modules, as well as the practical classroom considerations necessary to implement such modules, it was necessary to conduct a study that would provide feedback from participating students and instructors. In this chapter we will discuss the studies that were implemented as well as the methods through which the data from these studies was analyzed.

### **3.1 Maker Module Development and Impact Study**

The development of the maker modules was heavily reliant upon a design-based research method to iteratively improve the framework and structure of the maker-oriented learning approach described in this work. Through a collection of student-focused interviews and surveys, as well as discussions with instructors, and in-class observations, I was able to collect data that influenced this work in two necessary ways. The first, was in indicating deficiencies in early iterations of the maker modules, that allowed me to make necessary improvements to meet the needs of both the students and instructors participating in the modules. The second, was in indicating when those improvements led to desirable outcomes. This study was conducted at both Georgia Tech and Berry College as will be described in the sections below.



### *3.1.1 Data Collection at Georgia Tech*

The principle development of this work occurred within four courses being taught between 2015 and 2016 at Georgia Tech. In order to evaluate the efficacy of the maker module framework, I conducted a series of interviews with students participating in courses where the maker modules were implemented. This feedback proved to be the main impetus for modifying elements of the framework to better structure the activities for students.

During the Georgia Tech interventions, students were invited to take part in formalized interviews at the conclusion of the semester in order to gather feedback regarding the maker modules and the maker-oriented approach implemented in the classroom. This work was a subset of a larger study being conducted in the course. Throughout the four course offerings, 44 students (out of 207 total) participated in the study (Table 8). Students were offered extra credit in course if they participated in the interviews and the course instructor arranged for alternative extra credit opportunities for students that did not want to participate to minimize bias in participation [39]. Each interview took between thirty minutes to one hour, where students were asked to reflect on concepts such as transfer, self-reflection, communities of learners, as well as physical space and tools (the complete interview protocol is included in Appendix A). The audio of these interviews was recorded with the participants' consent per the Institutional Review Board research protocol and transcribed for further analysis [39]. This analysis took place in the form of coding the interviews to identify significant trends in the interviews. An initial code book was developed by three researchers participating in the larger study being conducted with the data and informed the process through which I was

able to evaluate the efficacy of the iterative changes taking place within the curriculum each semester [39]. The common themes that emerged from the transcriptions that were particularly relevant to this work included student reflections on the relevance of prototyping activities, amount of time spent participating in lectures versus activities, space utilization for prototyping activities, tool and material usage, and the value of in-class critiques. Specific selections from these reflections have been anonymized and included in the following chapters to provide evidence for the iterative changes that occurred throughout this study.

*Table 8 – Study participant breakdown by semester at Georgia Tech.*

<b>Course #</b>	<b>Course Name</b>	<b>Semester/Year</b>	<b>Total Students</b>	<b>Study Participants</b>
CS 3750	User-Interface Design	Fall 2015	68	15
CS 4605	Mobile and Ubiquitous Computing	Spring 2016	38	9
CS 3750	User-Interface Design	Fall 2016	69	13
CS 4605	Mobile and Ubiquitous Computing	Spring 2017	32	7

In addition to interviewing students on their experiences with the maker modules, instructor feedback was critical in developing the initial maker modules, as well as improving the modules through each course offering. This feedback was gathered in two significant ways. First, before the beginning of each semester, I met with instructors several times to discuss course objectives, expected learning outcomes, maker module implementation, and anticipated challenges with the modules. These anticipated challenges expressed by the instructors often gave rise to opportunities to evolve the maker module framework. Such challenges included the practical implementation of modules within traditional classrooms, establishing relevance of modules to current class topics, as well as the timing and order in which modules would be presented throughout

the semester. The second way in which feedback was gathered from instructors was throughout the semester. Discussions were generally held the week preceding each module session. During these discussions, instructors were able to express thoughts regarding the outcomes of the previous module as well as suggestions for the upcoming module. Most suggestions centered around anticipated difficulties with timing or class size, as well as focusing the modules to assist students in the completion of course assignments and projects. These suggestions were then documented and modules were updated to reflect any modifications. Each iteration of a module was saved as a distinct new version to enable a comparative analysis to be performed at the conclusion of the study.

A final source of iterative development for the maker module framework came from my participation in and observation of maker module sessions during classes. During the early development of maker modules at Georgia Tech, I actively participated in conducting maker module sessions. As the study continued, however, the role of conducting sessions gradually shifted to the instructor and I transitioned to an observational role. Active participation during early development allowed us to make dramatic modifications to modules, while later observations allowed us to make more fine-tuned adjustments to suit a variety of classroom environments and teaching styles. As this transition took place, the importance of developing a generalized framework became increasingly important to provide the necessary structure for instructors who were new to this maker-oriented learning approach.

### 3.1.2 Data Collection at Berry College

During the Berry College offerings, students were invited to participate in completing course evaluation surveys where they answered questions regarding their attitudes toward the relevance between class activities and course material, increased understanding of concepts, intellectual development, as well as strength and weaknesses of class activities. Throughout the six course offerings, 93 students (out of 127 total) participated in completing the course evaluation survey. These surveys were anonymously completed by students during the last week of each semester after all major work had been completed for the class (the complete survey protocol is included in Appendix B). No incentive was offered to students for completing the surveys, and participation was not mandatory. Using the significant themes gathered from the coding of the Georgia Tech interview transcripts, these surveys were similarly coded and excerpts included in the analysis given in the following chapters.

*Table 9 – Study participant breakdown by semester at Berry College.*

Course #	Course Name	Semester/Year	Total Students	Study Participants
CRT 101	Introduction to Prototyping	Fall 2015	17	15
CRT 101	Introduction to Prototyping	Spring 2016	23	9
CRT 101	Introduction to Prototyping	Fall 2016	19	9
CRT 101	Introduction to Prototyping	Spring 2017	20	17
CRT 101	Introduction to Prototyping	Fall 2017	23	21
CRT 101	Introduction to Prototyping	Spring 2018	25	22

In addition to completing course evaluations, Berry students were also invited to participate in an impact survey to assess the Creative Technologies program. This impact survey was part of a larger study being conducted but also used many of the same questions that appeared in the Georgia Tech interview protocol. Various elements of this

survey prompted students to reflect on the activities conducted during the Introduction to Prototyping course. A total of 18 students participated in this survey (the complete survey protocol is included in Appendix C).

In addition to the course evaluations and impact survey, I played the roles of instructor and observer in all six class sessions taught. In doing so, I was able to further iterate upon the maker modules based on observations made during the Georgia Tech sessions. This process allowed for a more rapid approach to iterating on the maker-oriented learning concepts as it was possible, in most cases, to implement two sets of modules each semester—one at Georgia Tech and one at Berry College.

### *3.1.3 Data Analysis Methods*

A large amount of descriptive qualitative data was gathered through the variety of student interviews and surveys completed, as well as notes from instructor discussions and research observations made during the modules. In order to determine significant trends in this data, a constant comparative method was used. This method is influenced by grounded theory and can be applied to qualitative data in order to identify phenomena in social settings, for example learning environments [50, 51]. In doing so, my goal was to identify students' and instructors' attitudes toward the implementation of the maker-oriented learning approach into classroom exercises, as well as to identify opportunities for maker modules to reinforce existing course concepts [39]. Because data was gathered after each treatment, the constant comparative method allowed me to examine the responses gathered from each round of interviews and use those insights in the development of the next treatment [51].

In the interviews administered to students from the Georgia Tech offerings, there were a few key questions in the protocol that were specifically examined using this method to address the research questions in this work. To preface, the research questions in this work are as follow:

*R1. What are the elements that should be considered when developing a framework for maker modules in human-computer interaction courses?*

*R2. What does a holistic curriculum of maker modules consist of?*

*R3. What considerations and practices are necessary when implementing maker modules in a traditional classroom and curriculum?*

*Table 10 – Georgia Tech student interview questions as they relate to research questions.*

<b>Interview Question</b>	<b>R1</b>	<b>R2</b>	<b>R3</b>
Was this class different than other classes you have taken? If so, how?	X		
What were your expectations in taking the course? Were those expectations met?	X	X	
What skills did you come into the class with that helped you? What skills did you need the most help on?	X		
Is there anything you learned in this class that might benefit you in your career?	X		
Did you get any new ideas or new projects based on what you learned in this class?	X		
Is there anything you learned in this class that helped you understand something outside of this class?	X		
Were there any in-class activities that helped you with your final project? If so, which ones and how did they help?	X	X	
What did you think about the hands-on in-class activities?	X	X	
How do you think these activities compare to lectures in class?	X		
Tell me about one time you had to work in a group during an in-class activity.	X		X
Is this classroom different than other classrooms? If so, how is it different?			X
What aspects of the classroom were the most useful during the in-class making activities?			X
What aspects of the classroom were most challenging to work with?			X
Did you rearrange any of the furniture in the space to make it easier for you to work?			X
How did the arrangement of the room affect your interaction with other people?			X
How well did the space work for critiques?			X
Is there anything you would change about the classroom?			X
Describe the challenges around working with the tools and materials during the maker activities.			X
Was there anything you wished you would have had during the activities?	X		X

Similarly, it was important to consider the feedback gathered from students participating in the Berry College offerings as well. In this case, student responses were gathered through written feedback from course evaluation surveys and the Creative Technologies impact survey conducted.

*Table 11 – Berry College student survey questions from course evaluations (CE) and impact survey (IS) as they related to research questions.*

Type	Survey Question	R1	R2	R3
CE	The graded work in this course was consistent with the content of the course that was presented, such in-class activities.	X		
CE	To what extent do you feel that you made significant gains in your understanding of the concepts explored in this class?	X		
CE	To what extent did you make significant gains in your intellectual development? This might include critically reading, critically thinking about issues raised in class, identifying patterns in data, writing documents, lab skills, or working with others.	X		
CE	Please describe the strengths of this course and the instructor. Try to be specific and give examples (e.g., textbook and other course materials, classroom activities, evaluations).	X	X	
CE	What recommendations would you suggest for improving this course?	X	X	
IS	Have this class been different than other courses you've taken in college? How?			X
IS	Have hands-on learning experiences affected your experience in this class?	X		
IS	Which hands-on activity had the most impact on your learning, and why?	X	X	
IS	Which hands-on activity had the least impact on your learning, and why?	X	X	

It was also important to consider feedback gathered from the instructors of the courses in addition to having a list of criteria for the researchers to make during classroom observations. This feedback was used to modify the maker modules and make it easier to implement them into constrained classroom spaces. Furthermore, the instructor feedback was essential in trying to assess the overall appropriateness of the modules as they related to overarching course concepts.

*Table 12 – Instructor discussion questions and research observation questions.*

<b>Discussion Questions</b>	<b>R1</b>	<b>R2</b>	<b>R3</b>
What course concept is this module trying to address? What are the specific learning goals for this module?	X		
What practical skills will help students with their class assignments or projects?	X	X	
What technology resources are available to the students? How will they access them?			X
What are the technical limitations of the teaching space? Does it have access to electricity, tables, writing surfaces, projectors, etc.			X
How long is each class session? How much time can be allotted for in-class activities?		X	X
How many students are in the class? Should students work alone or in groups?			X
What previous experiences do students in the class have?	X		
How will materials and tools be prepared for the classes. Where will they be kept?			X
How will students be evaluated on their work in the modules?	X		
What previous experience does the instructor or teaching assistants have?		X	X
Are students able to complete the in-class activities on time. What are they struggling with? What seems easy to them?	X		X
How closely do students' work resemble the desired outcomes for the activity?	X		
Are students using course concepts in the description of their work from the activities?	X		
How are students responding to the arrangement of tools, materials, and classroom infrastructure during activities?			X

The data gathered from student interviews and surveys, instructor discussions, and researcher observations was compiled after each semester and compared and contrasted, resulting in a series of recommended changes to the maker module framework, curriculum, and methods for implementation. It is these changes that will be detailed in the following three chapters as they address each of the research questions respectively.

### **3.2 Technology Diversification Study**

One of the main objectives of the maker modules and maker-oriented curriculum is to encourage students to adopt new technologies into their prototyping and design process. One of the central questions in this work was to determine the types of activities that would support curriculum-specific learning goals and to present those activities in an order that allowed students to build on previous experiences. In making these design decisions it was important to understand how students could incorporate skills learned in



the maker modules into their class assignments and projects. These design decisions and the effects they had on the maker module curriculum are discussed in Chapter 5.

In order to assess the selection of technologies taught in the maker modules and the order in which they were presented, I developed a technology diversification study that included every intermediate and final design project created by students in the six course offerings of the Berry College Introduction to Prototyping course. In each class, students were encouraged to consider their personal interests or hobbies and to think about a way in which they could make an improvement to those interests through the development of a tangible prototype. In doing so, many students' ideas centered around their lives as students, such as dorm room improvements, devices to assist in training as an athlete, or devices that helped them study better or wake up on time for classes.

Because of the very broad nature in which students were allowed to go about creating these prototypes, it became necessary to understand how the technologies addressed by the maker modules were playing a role in their creative process.

### *3.2.1 Data Collection at Berry College*

In total, this study looked at the skills and technologies used by 126 students to create 250 projects in this course and compared those to the topics covered in the eight maker modules to determine the relevance and order of the modules. The primary source of data for this study came from the project documentation created by students while they were creating their projects. This documentation consisted of project proposals, posters, and instructional guides called Instructables [52].

Prior to beginning on a project, students created a project proposal. In this proposal students were required to provide five key points of information. They include:

1. *Project Description* – Students are to write a description of the activity they are trying to improve through the development of their prototype. They are then to briefly describe the prototype’s function and how it will make that improvement.
2. *Related Work* – Students include three examples of existing work that has either influenced their prototype’s proposed design or is an existing method for improving the activity.
3. *Sketch* – Students must include a hand-drawn or computer-generated sketch of their own making that approximates the final form of the prototype.
4. *Resources* – Students create a comprehensive list of the tools, materials, and skills necessary to fabricate their prototypes. For each item on the list, they include its function, where they plan on accessing the resource, and their relative skill with the resource.
5. *Potential Challenges* – Students list three potential challenges that they make encounter during the production of their prototype.

For this work, the three most important elements of these proposals are the project descriptions, resources, and challenges sections. In these, it was possible to identify the resources and skills that students were planning on using in the development of their projects. This served as a reference point for evaluating the overall technologies

implemented in the maker modules. Students created a proposal for their intermediate projects around the third week of the semester, and another proposal for their final projects around the ninth week of the semester. As such, it was also possible to evaluate the timing of the maker modules throughout the semester as well.

Upon completion of their projects, students also created documentation detailing the process through which their prototypes were developed. For both the intermediate and final projects, students were given two options through which they could present this documentation. The first is through the creation of a project poster. Project posters are 11x17” printed posters that show both the completed prototype, as well as images and descriptions of the development process. Through this, it was possible to assess not just the final tools and materials used in the final prototype, but any additional tools and materials used by students in creating intermediary prototypes, such as an initial paper model. The second documentation method available to students is to create an online tutorial called an Instructable. Instructables is a website resource that allows users to create step-by-step tutorials showing how a project is made [52]. Much like the project posters, students that create an Instructable methodically detail the tools, materials, methods, and technologies they used in the creation of their projects. Because of this, it is a helpful resource in assessing the utility of the topics covered in the maker modules.

### *3.2.2 Data Analysis Methods*

The data for this project was acquired by assessing the technologies and prototyping methods used in each of the eight maker modules. I reviewed the documentation from each student’s proposal and documentation for their intermediate and final projects and

tracked the technology requirements of each project. I then mapped these requirements to the maker modules as included in Appendix D.

*Table 13 – Abbreviations for make module categories used in analyzing student projects.*

<b>Abbreviation</b>	<b>Title</b>	<b>Description</b>
<b>RP</b>	Rapid Foam Board Prototyping	Creating low-resolution paper-based prototypes
<b>2D</b>	2D Design	Using vector-based software to create graphics
<b>2F</b>	2D Fabrication	Using 2 axis CNC tools such as laser cutters
<b>3D</b>	3D Design	Using 3D design software to create graphics
<b>3F</b>	3D Fabrication	Using 3D printers to fabricate objects
<b>WT</b>	Wearable Technology	Developing devices meant to be worn on a body
<b>AR</b>	Arduino	Programming an Arduino microcontroller
<b>WW</b>	Woodworking	Using traditional methods to work with wood
<b>MW</b>	Metal Working	Using traditional methods to work with metal
<b>DT</b>	Deconstruction of Technology	Taking apart existing technology to modify its use
<b>CS</b>	Circuits and Soldering	Designing circuits and soldering components
<b>AF</b>	Advanced 2D Fabrication	Using a CNC wood mill for carving
<b>OT</b>	Other	Miscellaneous topics not covered in maker modules

*For example, for an intermediate project in Fall 2015, a student created a remotely enabled door opener as a result of frequently locking himself out of his dorm room (*

Table 14). The device itself consisted of an Arduino microcontroller that actuated a servo motor to pull down the door's handle to release its latch. It was housed inside of a laser cut acrylic case with a vinyl graphic affixed to the outside. The student also 3D printed additional gearing to multiply the servo's force to generate enough torque to open the door. Finally, he fabricated a wireless circuit that allowed him to actuate the system remotely that interfaced with a commercially developed mobile phone application.

*Table 14 – Example of mapping activities from a student’s project to the maker modules.*

<b>Project Activity</b>	<b>RP</b>	<b>2D</b>	<b>2F</b>	<b>3D</b>	<b>3F</b>	<b>WT</b>	<b>AR</b>	<b>WW</b>	<b>MW</b>	<b>DT</b>	<b>CS</b>	<b>AF</b>	<b>OT</b>
Programming an Arduino							X						
Interfacing with a Servo Motor							X				X		
Creating a Laser Cut Enclosure		X	X										
Creating a Vinyl Graphic		X	X										
3D Printing Gears				X	X								
Soldering a Wi-Fi Circuit							X				X		
Interfacing with Mobile App							X						X

This data provided an opportunity to look at what technologies would be the most useful for students to learn in the modules, as well as the correct time in the semester to offer the modules. Because in Introduction to Prototyping, students work on intermediate projects for the first half of the semester and final projects for the second half of the semester, it was important to consider the types of technologies students would select to use for each so that they could be introduced at the appropriate time. As such, through this iterative analysis, the types of maker modules, as well as the order in which they were presented, evolved over time (Table 15).

*Table 15 – Order of maker modules taught during six offerings of Introduction to Prototyping course at Berry College.*

<b>Offering</b>	<b>#1</b>	<b>#2</b>	<b>#3</b>	<b>#4</b>	<b>#5</b>	<b>#6</b>	<b>#7</b>	<b>#8</b>	<b>#9</b>	<b>#10</b>	<b>#11</b>
Fall 2015	DT	RP	WT	3D/3F	2D/2F	WW	AF	CS	AR		
Spring 2016	RP	2D/2F	3D/3F	WT	WW/MW	CS	AR	DT	AF		
Fall 2016	RP	3D/3F	2D/2F	WT	WW/MW	AR	DT	CS	AF		
Spring 2017	RP	3F	2D/2F	3D	WT	WW/MW	AR	DT	CS	AF	
Fall 2017	RP	3D	2D/2F	3F	WT	AR	WW	MW	DT	CS	AF
Spring 2018	RP	3D	2D/2F	3F	WT	AR	WW	MW	DT	CS	AF

Through tracking what technologies students were using each semester and comparing it to the topics and timings of the modules, I was able to generate trends that would help shape the maker modules for each successive semester. These trends were corroborated with feedback gathered from student course evaluation surveys, as well as instructor observations in order to determine a final offering.

## CHAPTER 4. MAKER MODULE FRAMEWORK DEVELOPMENT

The introduction of physical prototyping activities into traditional classrooms can be a daunting task. The thought of conducting in-class activities that heavily rely on tools, equipment, and materials, while constrained to limited space and time can be a difficult undertaking. Furthermore, a considerable amount of time must be spent in ensuring that the activities have relevance to the underlying course objectives and allow the students to make strong ties between concepts and practices. As I have undertaken those challenges, a number of structural elements have emerged that have allowed me to create a framework that organizes these maker modules in a way that is consistent, effective, and topical to the learning objectives of the courses in which they are taught. This process of identifying these elements was iterative and has come in response to instructor and student feedback, as well as through researcher observations.

The purpose of this chapter is to answer the first research question: *What are the elements that should be considered when developing a framework for maker modules in human-computer interaction courses?* I will address this question in two parts. The first will identify the structural elements and show the foundational role each of them plays in a successful maker module. The second part will then show how these elements were identified through research interviews and surveys and detail the chronology in which they were developed. The value in sharing this chronology, will be to illustrate methods in which curricula can adapt overtime to better suit its instructors and students. These

methods will prove useful as one seeks to adapt the maker modules recorded in this work, as well as in the development of new maker modules for other courses.

#### **4.1 What structural elements are required to make a maker module successful in the classroom?**

As explained in section 2.2, a total of eight maker modules were developed as part of this work. Organizing these topics and activities into a standard format in which they could be presented proved to be challenging. These challenges arose out of the apparent dissimilarity across many of the activities. For example, in Rapid Foam Board Prototyping, students rely on simple hand tools to create non-functional lamp prototypes, whereas in Interactive Prototyping with Arduino, students are using computers, microcontrollers, and electronic components to create interactive circuits. However, it became critical to create a standard format through which these topics could be taught in classrooms for the benefit of both the instructors and students.

A standardized format of the modules enables instructors to focus on ensuring that maker modules meet the anticipated learning goals of the course. By creating a framework through which the activities in the modules can be related to theoretical topics in the course, instructors can develop activities that will engage students and reinforce complementary course content. Furthermore, it also reduces the amount of preparation time needed to implement such activities in classes. The standardized format is designed to benefit students as well. Because the maker-oriented learning approach may be new to many students, having a set format for each of the modules will help them anticipate



instructor expectations and learning objectives, especially when the material or methods seem foreign or new.

#### *4.1.1 Elements of the Maker Module Framework*

Each maker module follows a similar flow, to allow instructors and students to follow a consistent pattern. This pattern was developed iteratively through design-based research methods as described in section 3.2.

It begins with the introduction of a relevant prototyping topic and its connection to human-centered design. This introduction is meant to familiarize students with the concepts and vocabulary necessary for them to develop a working knowledge of the subject and prepare them for skills development. The next section is a warm-up activity that procedurally walks students through a constrained set of steps to familiarize them with the tools necessary to develop physical prototypes. After the warmup activity, students are then presented with a design challenge. This problem-based challenge is designed to allow students to combine the foundational knowledge learned at the beginning of the session with the skills learned during the warm-up activity. The result is an opportunity for students to create an original physical artifact through an exploratory design process.

While the creative aspects of these design challenges are open-ended, I have developed a strict framework through which students are to complete the challenges. This framework constructively constrains students to assist them in making connections between the concepts and skills covered in the module. It consists of five distinct elements: *expectation*, *exposition*, *exploration*, *explanation*, and *expansion*.

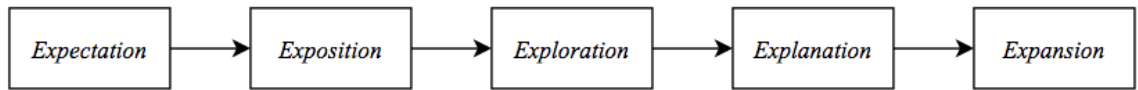


Figure 3 – The five elements of the maker module framework.

During *expectation*, students are giving a clear description of the learning goals for the design challenge. This is meant to provide a justification for why they are about to do the prescribed activity and creates a set of expectations that they can reflect on at the conclusion of the activity. In *exposition*, the instructor provides an extensive amount of background information necessary for students to understand the design scenario in which they are being placed. In this step there may be additional terms or industry-specific knowledge passed on to the students to ensure they understand the requirements, limitations, and opportunities within the module.

During *exploration*, students begin their creative work. This step generally begins with idea-generation exercises such as creative brainstorming, internet research, informal interviews, and sketching. After idea generation, the students are then given a directive to fabricate a physical prototype using the prescribed technologies discussed in the module. Often times, the exploration step is time constrained to help keep the work moving. In many of the modules, this step is structured such that most, if not all, of the work can be completed during a 90 or 120-minute class session. At the conclusion of exploration, students then proceed to *explanation* where they reflect on their work and how it connects the concepts and skills learned in the course. This reflection is often conducted as a brief

in-class presentation that allows fellow students to assess and critique the work. When necessary, however, these reflections can be completed as an out-of-class assignment.

Finally, students will complete an *expansion* step where they will extend what they've learned during the challenge to an external experience. This allows them to transfer knowledge from the design experience to other assignments, classes, or experiences that they have had. This is especially applicable for courses that include a significant class project that extends throughout the semester.

## **4.2 How were the elements of this framework developed through the maker modules?**

As outlined in section 2.2, the development of this framework was created iteratively through design-based research over the course of seven semesters. Each iteration of the framework was affected through information gathered from student interviews and surveys, discussions with instructors, and observations that I made during maker modules. To illustrate the development process, I will present a case study through the Rapid Foam Board Prototyping module that was developed.

### *4.2.1 Framework Development through the Evolution of the Rapid Foam Board Prototyping Maker Module*

In order to illustrate the development of the maker module framework, I will present the development of the Rapid Foam Board Prototyping module across seven evolutions. In this chronology, I will demonstrate how feedback gathered from student interviews and surveys, instructor feedback, and research observations prompted the

development of this framework. While a similar evolution occurred with many of the maker modules, this example is the most comprehensive and illustrative of the process that was undertaken.

Each evolution of this module represents a chronological offering of the curriculum. In some cases, the module was taught concurrently at both Georgia Tech and Berry College as detailed below (Table 16).

*Table 16 – Chronology of Rapid Paper Prototyping module evolutions.*

<b>Iteration</b>	<b>Semester/Year</b>	<b>Georgia Tech Course</b>	<b>Berry College Course</b>
I	Spring 2015	Mobile and Ubiquitous Computing (MUC-S15)	---
II	Fall 2015	User-Interface Design (UID-F15)	Introduction to Prototyping (ITP-F15)
III	Spring 2016	Mobile and Ubiquitous Computing (MUC-S16)	Introduction to Prototyping (ITP-S16)
IV	Fall 2016	User-Interface Design (UID-F16)	Introduction to Prototyping (ITP-F16)
V	Spring 2017	---	Introduction to Prototyping (ITP -S17)
VI	Fall 2017	---	Introduction to Prototyping (ITP -F17)
VII	Spring 2018	---	Introduction to Prototyping (ITP -S18)

In the following subsections I will discuss how each element of the maker module framework was created through documenting its development and refinement through the seven evolutions of the Rapid Foam Board Prototyping module. Within each section I will briefly discuss what each framework element entails, how it is implemented in the module, and the evidence from the research that prompted the creation and iteration of each element. A summary of those iterations is included in the following figure (Figure 4).

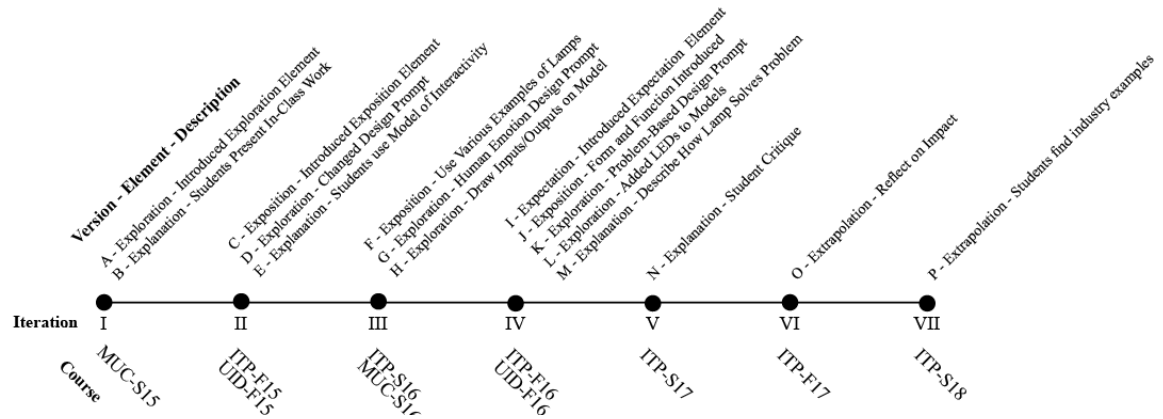


Figure 4 – Summary of maker module framework elements in Rapid Foam Board Prototyping module.

#### 4.2.1.1 Framework Element I: Expectation

The expectation element of each module provides students a clear description of the learning goals associated with the activities for the day. By clearly laying out the expectations at the beginning of the module, it allows students to anticipate and understand how the activities will further their understanding of the course content.

In the Rapid Foam Board Prototyping module, this is demonstrated by discussing the importance of a model of interactivity (as described in 2.1.2.2) as it pertains to everyday devices, such as a desk lamp. Students were told that upon completion of the module, they should have an increased understanding of the model of interactivity by working through a creative design process to develop their own interactive lamp concept by using foam board construction.

The discussion of the model of interactivity was initially absent in iterations I, II, and III of the framework. Its importance became evident during student interviews during the second and third iterations of the module. When asked how students felt the maker

module activities related to the overall course concepts it became apparent that there was a disconnect between the two. For example, one student stated:

*I did not think I got a lot out of it. Everything was kind of jumbled together. It's like two classes in one. There were concepts and there was group work, and I do not think we learned a lot about user interfaces. (UID-F15)*

This type of response was typical during early development. The transition between standard lectures and hands-on activities were initially jarring for students and many were not sure why they were building physical prototypes in a course that was primarily focused on user interfaces. While students seemed to enjoy the activities, it was unclear why this new approach would be used in a computer science curriculum:

*The most fun was hand-making the prototype. I do not know how applicable that is for computer science though. I thought it would be more digital and user experience (UX) things and not physical prototyping things. I was not expecting that, but I liked it, but I do not think everybody thought it was relevant to UX.*

(UID-F15)

To respond to this, I introduced the expectation element during Iteration IV in both UID-F16 and ITP-F16 as seen in Version I. The inclusion of a justification of how the modules related to overall course content improved the class experience afterward. This trend emerged in the courses that followed the implementation of this element. When asked about the overall strengths of the course, a student responded:

*The classroom activities in this course were great and really helped me to understand what was going on in the class. (ITP-F17)*

This was furthered by another student to include not just the curriculum topics, but also the course project as well:

*In-class activities based on the readings helped solidify my understanding of the topics covered in each chapter and helped relate them to the projects that we were working on. (ITP-F17)*

Since its introduction during Iteration IV, the expectation element has continued to be included in the curriculum to help students understand the connections between the maker module exercises in the context of the overall course curriculum.

#### 4.2.1.2 Framework Element II: Exposition

For many students, a maker-oriented learning approach may be an unexpected or new experience among their other classes. As such, the exposition element provides student with additional background information or basic skills in which they are able to develop meaningful work. For example, in a 3D printing and design module, it could include a brief history of the development of 3D printers to help students understand the fundamentals of the process by discussing the evolution of the technology. It could also

include a guided warm-up activity in 3D design software to help students become familiar with basic software operation through the creation of simple geometric shapes.

In the Rapid Foam Board Prototyping module, the exposition element serves three purposes. The first purpose is to demonstrate to students how rapid prototyping is frequently used as an idea generating and sharing exercise. Because these modules are often situated in courses where students will be working on project- and problem-based assignments, the ability to rapidly create concepts can be a useful skill to develop. In this section, students learn the three fundamental criteria for rapid prototyping methods, i.e. methods should be fast enough to allow for multiple iterations, materials should be inexpensive to curtail the sunk-cost fallacy, and prototypes should be “good enough” to convey a complete design idea but avoid unnecessary features [53].

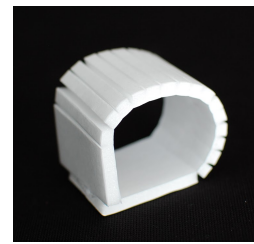
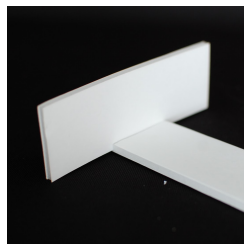
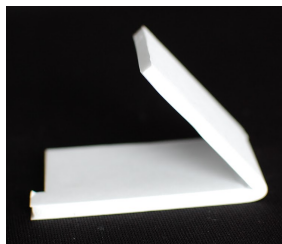
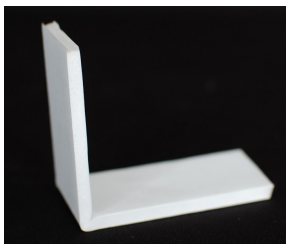
The second purpose is to help students understand how form and function can influence each other. This is achieved by revisiting the model of interactivity discussed previously during a standard lecture and discussing how the form of everyday technologies influences a device’s function. In this case, students are challenged to examine and discuss several types of lamps as a way to prepare them for creating interactive lamp prototypes during the *exploration* element (Figure 5).





*Figure 5 – Students compare and contrast the role of form and function among three interactive lamp concepts (left to right): a desk lamp, an animatronic lamp, and a light-sensitive night light.*

The third purpose is to familiarize students with basic tool use and fundamental construction techniques using the foam board. The tools used in this module are relatively simple, though many students may have little experience with them. Basic safety is discussed in relation to the hot glue guns and X-Acto knives, and students are introduced to the physical properties of foam board. The instructor then demonstrates four simple joints that allow students to create a variety of forms using the foam board (Figure 6). Students are then invited to recreate those four joints to familiarize themselves with the tools and materials.

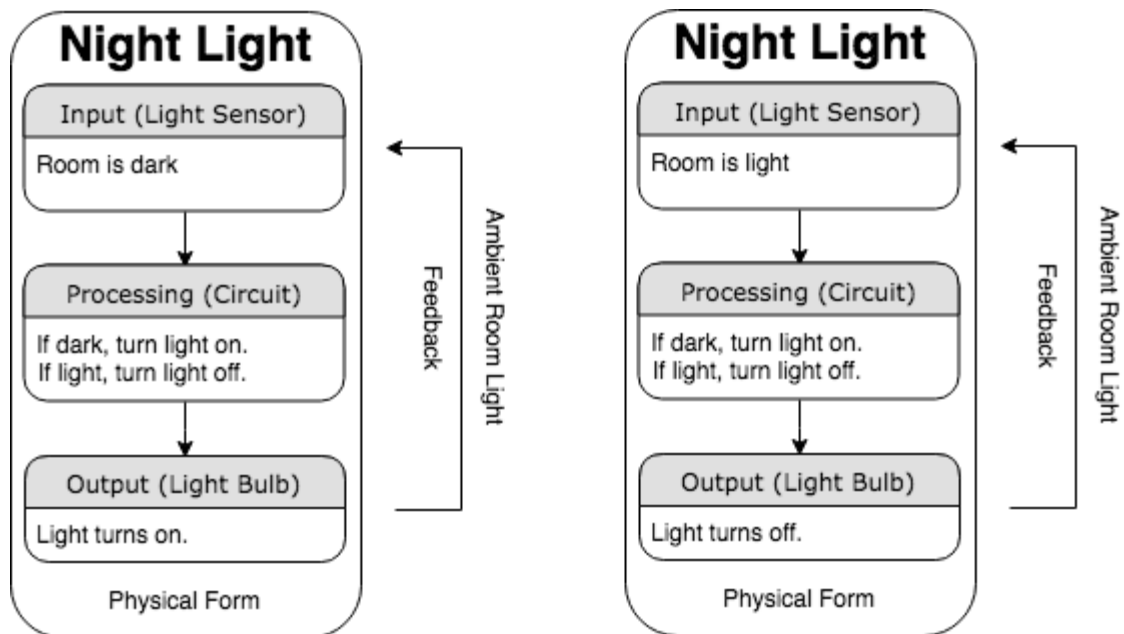


*Figure 6 – The four basic foam board joints (left to right): sharp joint, small radius, lap joint, and large radius.*

This element was introduced early on in the development of the maker module framework because it quickly became apparent that students lacked the experience with the tools, and the ability to apply abstract course concepts to hands-on activities (Version C). While it was originally introduced in Iteration II, this element was revised subsequently in Iterations III and IV. These iterations allowed me to create a three-part structure wherein students are provided the necessary knowledge and experience to participate in a hands-on exploration (as described in the next section). This three-part structure includes connecting the module to existing course concepts and assignments (e.g. rapid prototyping for idea generation and model of interactivity), providing a context in which students are able to evaluate work based on the criteria and vocabulary of course concepts (e.g. comparing three examples of interactive lamps with respect to form and function), and developing basic skills with tools, methods, and materials (e.g. practice creating basic foam board joints).

The primary catalyst for these changes came from instructor discussions and researcher observations of students' performance during the exploration element. Prior to teaching the module in UID-F15, the course instructor decided that it would be more beneficial for students if the Rapid Foam Board Prototyping module more closely tied in with the principles of interactivity previously discussed in class. As a result, I included an example of a desk lamp and animatronic lamp to provide a context through which students could discuss how information moves through inputs, processing, and outputs in an interactive device, as noted in Version F.

As a result of students presenting their paper prototypes in UID-F15, however, I observed that while students were able to adequately explain the interactive functions of their work, they were often unable to justify how the physical form of the device influenced or was influenced by the functions. To address this concern, an example of a light-sensitive night light was added to demonstrate the relationship between form and function (Version J). In the case of the night light, students discuss how the form of the light enclosure and the placement of the light sensor on the night light prevents the device from entering a feedback loop where it senses its own emissions instead of the ambient light from the room (Figure 7).



*Figure 7 – A model of interactivity for a night light shows two possible outcomes.*

The inclusion of this element has improved the overall flow and structure of the maker modules. By engaging the students in a discussion of how the module connects

with course topics and allowing them to participate in a warm up activity, students were better able to relate their own creations to course topics and required fewer interventions during the *exploration* element with concerns about how to use the tools or materials.

#### 4.2.1.3 Framework Element III: Exploration

The exploration element of the maker module framework is fundamental to the constructionist influence for the maker-oriented learning approach. By allowing students to engage in hands-on activities, students can develop their own understanding of the course concepts [9, 22]. Explorations are generally structured as constrained design exercises that include idea generation and prototyping to allow students to create a physical artifact that manifests elements of the underlying learning goals of the course. Creative constraints are incorporated into the activities to both scaffold the students' work as well as to narrow the scope of activities to ensure each module is manageable for instructors to teach. For example, thematic constraints in design activities allow students to explore problem-based designs and can be narrowed to domains that are familiar to the instructor and relevant to the course. Time constraints similarly help students focus on core fundamental ideas without pursuing extraneous features, while simultaneously assisting the instructor in constraining the modules to single class sessions. In general, modules generally fit well within 90 to 120-minute class sessions, though they can be adapted for 50-minute class sessions as will be discussed in Chapter 5.

Within the Rapid Foam Board Prototyping module, the *exploration* element builds off of the previous discussions regarding the model of interactivity, creative lamps, and the foam board construction techniques covered during the *exposition* element. Lamp

making was chosen because of the interest of interactive lighting by some of the instructors, as well as most students' familiarity with such devices. In other implementations, this could be adapted to a variety of familiar, everyday objects.

This *exploration* element begins with a simple prompt for students to arrange themselves into small groups (generally 2 to 5 students per group) and consider personal interests and hobbies and brainstorm problems within those interests. Problems are broadly defined as anything that could be improved, made easier, personalized, or allow new audiences to engage with the interest. After an initial brainstorming period, students are challenged to discuss and sketch concepts of interactive lights that could help address those problems. They are instructed to consider how sensors and actuators would function within the concepts and are advised to keep sketches simple and constrained to the materials provided within the exploration (foam board, hot glue, X-Acto knives, and LEDs). They are encouraged to think broadly about creative solutions and should not dismiss radical or improbable design ideas. An example problem scenario is proposed: "How does one know when they have a good idea?" A sample solution is shared of an oversized lightbulb suspended above someone's head that uses EEG sensors to scan a user's brainwaves and lights up the bulb whenever the system senses a good idea. While this proposed design is not technologically feasible, it demonstrates to the students the creative flexibility they have within the activity.

After this brief idea generation session, students are then instructed to select one of the ideas discussed and begin fabricating the idea using the supplied materials. Because the prototypes are conceptual and non-functional, students are encouraged to draw

sensors, user-interfaces, and actuators onto the foam board models to help them convey the design concept.

With respect to the evolution of the maker module framework, portions of the exploration element were present from the beginning. However, throughout its implementation, six significant changes were made to address student feedback, instructor discussions, and researcher observations. In the original implementation of this module, students created a mug based on an image shown to them (Version A). The idea behind this was to very narrowly constrain the students to practice precision by emulating an existing design concept. While this was moderately successful in helping students become more comfortable with the tools and materials, it did not complement the course concepts. Prior to Iteration II, the ITP-F15 course instructor suggested making something that would allow students to explore elements of the model of interactivity. It was then decided that students would be allowed to create an interactive lamp instead (Version D). In this version, very little guidance was given, though students were encouraged to consider some creative application for their lamps.

After the implementation of the interactive lamp in Iteration II, I observed a large variance in how students interpreted the challenge. In both UID-F15 and ITP-F15, some student groups recreated simple desk lamps as shown as part of the discussion. To address this, I modified the prompt to emphasize a human-centered design approach in Iteration III (Version G). This prompt encouraged students to “Define an emotion and design a lamp that expresses it.” This prompt, however, was met with confusion and required a number of instructor and researcher interventions during the brainstorming and

design process to explain the prompt and help students modify their designs to satisfy the criteria of the assignment.

In addition to modifying the prompt during Iteration III, I also implemented a technical requirement for the interactive lamp concepts. In many post-course interviews, students indicated their dissatisfaction with how some of the maker modules aligned with the course topics. This was especially present after the UID-F15 course offering that explored elements of user-interface designs. As expressed by one student:

*“The title of the class is a little bit misleading -it’s User Interface Design and we didn’t really learn about that with the activities.” (UID-F15)*

In order to address these concerns, I modified the activity to require students to sketch sensors, user interfaces, and actuators onto the prototypes to reinforce the relationship between these elements and the physical form (Version H).

In preparation for Iteration IV, the instructor and I decided to address the confusion associated with the design prompt for students to design a lamp that expressed an emotion. While the intention to more creatively constrain students’ ideas and tie them more closely to course concepts was appropriate, it was decided that a problem-based approach may be more suitable and relevant to the semester-long projects being undertaken by students in the classes. Therefore, the prompt was modified to require students to consider personal interests or hobbies and identify an improvement that could be made in that domain through the development of an interactive light (Version K). This resulted in both a decrease in the amount of time required for students to brainstorm—

previous sessions had allowed 15 minutes for brainstorming and sketching, whereas only 10 minutes were required under the new prompt. Furthermore, there was a reduced incidence of instructor or researcher intervention in groups to clarify the prompt during the brainstorming or production exercises. Students responded positively as well:

*When we are doing the hands-on prototyping I thought it was interesting because we just immediately came up with a million ideas and it gave me an idea of what it really meant to do really fast prototyping based off of a bunch of ideas, and the range of results that you could get. I think that's the biggest take away from the class. (UID-F16)*

One final addition made to the execution of the module was implementing basic technologies into the activity to allow students to better express their design concepts. During MUC-S16 and ITP-S16 it was observed that some students were using the flashlight capabilities on their mobile phones to illuminate their prototypes during their brief presentations. This improvised approach allowed them to better illustrate the role that light was playing in their designs. To enable this functionality among all students, I introduced LEDs and coin cell batteries that could be easily affixed to prototypes in Iteration IV (Version L). One interesting observation made in subsequent iterations of this activity was a process of active bartering between groups to procure LEDs of a certain color (a variety of colored LEDs were distributed). Groups would seek out certain colors of LEDs that they felt better expressed the functionality they were trying to demonstrate.



While it seemed obvious at the beginning of this work that exploration would be a foundational step in the maker-module framework, through the iteration of this element across several semesters, I was able to improve the module significantly to better address the needs of the instructors and students in reinforcing course concepts through the hands-on activities.

#### 4.2.1.4 Framework Element IV: Explanation

One fundamental aspect of constructionism is the idea that learning can be facilitated through students reflecting on their designs [54]. By allotting students an opportunity to present their creative works after the *exploration* element, they are given an opportunity to justify their design decisions within the context of the course. This is beneficial for both students and instructors. For students, it gives them an opportunity to evaluate their own work and compare the expected outcomes to the actual results. It also allows them to practice using content-specific language and explain theoretical concepts as they apply to their work. Furthermore, it gives them a chance to evaluate and critique their peers' work in the classroom. For instructors, this element provides a contextualized scenario where learning outcomes can be evaluated. For example, if during a presentation a student swaps the meanings of a “signifier” and “affordance” (a common mistake among students in HCI-courses), the instructor can correct the mistake within the bounds of a contextualized artifact in the student's hands. In addition to in-class opportunities for explanation, it is often times appropriate for students to complete a written reflection on their design process as well.

Much like the *exploration* element, this framework element was present in the maker modules from Iteration I. Similarly, within the Rapid Foam Board Prototyping module, it underwent significant revision to accommodate improvements made with the rest of the framework. Initially students were given a brief 30 seconds to show what they made and discuss any difficulties they had in making it (Version B). As the nature of the exercise evolved to include a more robust approach to address course topics, it became necessary to prompt students to speak about how their prototypes reflected these ideas. For example, in Iteration II, the explanation prompt was modified to encourage students to explain how their design fits the model of interactivity. As a result, students began incorporating descriptions about sensors, processors, and actuators in their presentations (Version E). Because time limitations were still a factor in large classes, these presentations were kept brief (60 seconds each), but students were required to complete an out-of-class reflection discussing their lamp's function and how it conforms to the model of interactivity.

During Iteration IV, the presentation prompt was further revised to prompt students to justify not only why their concepts fit within the model of interactivity, but also address the problem-based design challenges they brainstormed during the idea generation portion of the *exploration* element (Version M). Starting in Iteration V, I began introducing very basic elements of peer critique into the *explanation* element as well. For each presentation, students were prompted to consider one feature of each prototype they thought matched the assignment requirements well, as well as one feature that they felt could be improved or iterated upon to better match the requirements (Version N). In doing so, students were able to begin the conceptual process of seeing

how they could iterate upon their designs to bring them into closer accordance to the course concepts.

While the *explanation* element has the highest degree of variability given class sizes and time limitations, the benefits of having students share their work with the class was illuminating for both the instructor and students.

#### 4.2.1.5 Framework Element V: Expansion

In addition to connecting the maker modules to the underlying course concepts, I also wanted to provide opportunities for students to connect what they were learning in the modules to other assignments, courses, and external experiences. In some cases, it can be difficult for students to see how in-class activities apply to a variety of experiences. The expansion element of the maker module framework is intended to help students identify these relationships and transfer knowledge between the modules and external experiences.

Initially the expansion element was not formally introduced to the maker module framework until Iteration VI. However, at various points during the development of previous iterations, it became apparent through student feedback that it had the opportunity to play a significant role in the modules. For some students, the applicability of the modules was not particularly well stated or clear. This was particularly evident in the User Interface Design courses (UID-F15 and UID-F16). When asked about the usefulness of the modules, typical responses included:

*A lot of the activities in the classes were very physical, like the 3D modelling, and we did not use any of that in our final project. UID-F15*

*Since my final project was just a website, there were no hands-on projects that really helped me. The hands-on stuff was really fun and definitely inspired me to do a lot, but it didn't help in my final result. UID-F16*

In these cases, students felt that the maker modules had little bearing on their final projects because they were developing software-based prototypes. Other students felt that there was little relevance of the modules because of larger issues such as real-world application or career goals. For example:

*In this class, it felt like we weren't getting any real-world application. In my other classes we have lots of examples of real-world things we could relate to. UID-F15*

*I'm looking to do software engineering, so I didn't get a lot of application for that out of the activities. UID-F16*

However, these concerns were not universal across all courses. Students in more device-centric courses such as Mobile and Ubiquitous Computing (MUC-15 and MUC-16) had a different view, such as:

*Our project is doing a real prototype. A real physical prototype. We never would have come up with that had we not done the foam board exercise. MUC-15*

*We learned a lot about how to actually create things from scratch. I had no idea how to create or how to conceptualize a wearable before this. So, that was helpful for the end of the semester project. Pretty much all the things we learned at the beginning of the semester, we just applied it on the final project. MUC-16*

In addition to assisting students with their final projects, students also found relevance for both software and non-software related career applications. For example:

*This class was also different in the sense that there are very few other classes that focus on design in general. This is useful because in the future when you have to build software, knowing design in your job is very important. MUC-15*

*A lot of the stuff I want to do is not so much about user interface design, but it's about developing tools to fix problems that people have, so I think that it was extremely helpful. I'm absolutely sure I am going to use it. I can't say that about every class I've taken. MUC-15*

After considering the variety of mixed responses from students, I decided to formally address the role of the maker modules through two out-of-class assignments. The first was introduced in Iteration VI in the ITP-F17 course (Version O). In addition to

reflecting on how the prototype conforms to the model of interactivity (as detailed in section 3.2.2.4), students were prompted to briefly explain how the maker module could play a role in the development of their semester-long projects. At the conclusion of this course, students responded positively with respect to finding opportunities to apply the concepts covered within the modules to outside influences, such as other classes or technologies encountered outside of the classroom:

*The strongest example that I can think of was when we took apart devices and then explained how they worked. It was very informative and gave us a chance to see how the ideas within this course apply to the real world. That's something that this whole course does well. ITP-F17*

*I now know how to use tools and software that I didn't know existed before coming to this class. I have already applied some of what I learned in this class in my other classes. ITP-F17*

In Iteration VII, a final addition was made to the reflection. In this iteration students were further prompted to find two examples of how the skills learned in the modules are used by professionals in industry (Version P). As was the case in the previous iteration, students also commented on their ability to find connections between the module concepts and external activities:

*The strengths of this course revolve around the fact that all the activities we do can be used in the real world. ITP-S18*

*This class helped me to significantly increase my hard skills and allowed me to add several things to my resume. ITP-S18*

A significant takeaway from the development of this module is that a significant amount of consideration should be taken when developing modules to find opportunities for students to make connections between the course material, maker module concepts, and external contexts. For courses that are device-centric such as Mobile and Ubiquitous Computing as well as the Introduction to Prototyping, these connections may come more naturally to students because of the inherent physicality of such courses. In other HCI courses that generally trend toward more software-based work, it can be beneficial for instructors to emphasize common principles (such as user-interface sketching as discussed in section 3.2.2.3) to assist students in making meaningful connections.

### **4.3 Discussion**

Throughout the development of this maker module framework, a number of improvements were made using design-based research methodologies. Each iteration was heavily influenced through the evaluation of student interviews and surveys, instructor discussions, and researcher observations. In this study I focused on the development of the maker module framework through the lens of how the Rapid Foam Board Prototyping module evolved, similar patterns emerged across the other maker modules as well.

The development of this framework has been useful in further developing each of the maker modules, as well as in the creation of additional maker modules. By identifying the five elements of a module—*expectation*, *exposition*, *exploration*, *explanation*, and *expansion*—it has provided a set of guidelines that allow instructors to introduce maker-oriented activities into their courses that will reinforce core course concepts. Furthermore, it will allow students to implement those concepts into applied, hands-on work and explore further application of such concepts in other class assignments, other courses, and even in external contexts such as internships or jobs.

As discussed in Chapter 2, this approach is deeply rooted in Project-based Learning and Problem-based Learning. However, there are additional learning models that can help situate the Maker Module Framework in establishing its role in helping establish learning objectives in the class curriculum. Design-based Learning (DBL), for example, uses an inquiry-based learning approach in order to help students learn course concepts through an iterative design process [55-57]. One fundamental aspect of DBL is that student learning is supported through the creation of artifacts that demonstrate understanding and situate ideas in a more concrete context [55]. It achieves this through encouraging students to fabricate, evaluate, and refine their artifacts as they develop additional understanding or knowledge about their subject area [56]. This approach informed the development of the Maker Module Framework as modules evolved from individual in-class prototyping activities, to a cohesive part of the course that influenced various elements of the curriculum including lectures and semester-long projects. While comparative outcomes between the maker-oriented approach in the HCI courses were not



studied against traditional approaches within the scope of this work, a DBL approach in classroom instruction can result in positive learning outcomes [58, 59].

Another learning model that has been used in computer-science and HCI instruction is Bloom's Taxonomy, which defines six objectives in a knowledge-based cognitive domain including knowledge, comprehension, application, analysis, and evaluation [60-62]. The knowledge objective, as described by Bloom, describes the process through which students are introduced to basic concepts without the students developing an robust understanding of what those concepts mean [60]. The *exposition* and *explanation* elements closely follows this objective insomuch that students are being introduced to new and unfamiliar concepts to which they have not previously experienced and may not fully understand. Bloom's comprehension objective, as described by Bloom, allows students to use the knowledge they have acquired in order to organize or interpret learned concepts within a specific context, whereas his application objective describes when students apply those concepts to new situations using what has been learned [60]. These objectives help describe some of the underlying objectives in the activities that take place during the *exploration* element of the framework. During the guided warmup activities, students are given the opportunity to demonstrate their basic understanding by completing well-constrained tasks that situate the course concepts into simple physical artifacts. Upon completion of these tasks, students then are presented with an open-ended challenge that requires them to brainstorm and fabricate an artifact using that knowledge in a new context. Furthermore, Bloom describes the analysis and evaluation objectives as the ability to support one's conclusions with evidence and being able to make values judgements regarding design decisions and outcomes [60, 62]. Within the module

framework, students have an opportunity to explore these objectives during the *explanation* element as they are given the opportunity to not only present their work and describe how their physical prototype embodies the concepts being discussed that day, but also are given the opportunity to critique other students' work and evaluate how strongly the design objectives were met. Finally, Bloom describes synthesis, an objective in which the individual elements of knowledge are understood as part of a larger system [60]. This objective is most closely embodied in the *expansion* element in that students are encouraged to explore how the concepts and skills learned that day apply within the greater context of the course, a semester-long project in progress, or even their future careers in industry.

#### **4.4 Conclusion**

The development of the maker module framework with its five distinct elements represents a significant contribution to instructors that are incorporating maker-oriented activities into human-computer interaction courses. This framework provides a method of developing strong connections between the underlying course learning objectives and the hands-on classroom activities. This is achieved through the *expectation* element by allowing students to see how the maker modules connect to existing course material, as well as the *expansion* element which allows them to discover applications both within the course and external contexts. The framework also eases the burden on instructors and students that may be new to maker-oriented learning curriculum by procedurally introducing concepts in way that continuously builds on top of simpler concepts. This procedural learning is centralized in the *exposition*, *exploration*, and *explanation*

elements that allow for constrained activities to gradually widen in scope to build skills and confidence. As such, the maker module framework establishes a logical flow and rhythm of instruction that can be implemented, not only with the modules described in this work, but also a broad variety of maker-oriented technologies or activities. Thus, the overall impact that this contribution has in the field of maker-oriented learning is demonstrated because the principles of this framework enable instructors to develop and implement new modules into their curricula.

## **CHAPTER 5.     MAKER MODULE CURRICULUM DEVELOPMENT**

Throughout Chapter 4, I explored how the individual elements of the maker module framework were developed iteratively through the implementation of one of those modules. However, it is also important to consider how a broad collection of maker modules was created and integrated into a comprehensive curriculum that can be utilized in HCI-based courses. Thus, this chapter will seek to address the second research question - *What does a holistic curriculum of maker modules consist of?*

In order to answer this larger question, I will explore the origins of the holistic maker module curriculum and illustrate its iterative development through the analysis of data gathered from student surveys and project documentation, as well as instructor observations. In doing so, I will show how instructors and universities can assess their technology resources in order to determine what maker modules may be the most appropriate to introduce into classrooms. I will also demonstrate how the holistic maker module curriculum provides a scaffolded approach for students to develop physical prototypes. Finally, I will discuss how the order in which maker modules were taught in the courses evolved over time to better suit learning outcomes and support student work.

### **5.1     Assessing Institutional Technology Resources to Develop Maker Modules**

Throughout the development of this work, it was important to consider the existing technologies available to instructors and students in order to develop tools and equipment that would facilitate the maker-oriented activities introduced in this work. In

doing so, it was possible to develop maker modules that not only supported course learning objectives, but also worked within the limitations of what was currently available on campus to use. As such, I approached the tools and resources of each university campus (Georgia Tech and Berry College) as a creative constraint in which to develop the modules.

A technology assessment of Georgia Tech revealed a variety of facilities that were capable of supporting maker-oriented activities through physical prototyping. The largest and most well-known of these is the Invention Studio. The Invention Studio is a centralized space that provides a wide variety of tools that are available to students and faculty free of charge. It is largely staffed by student volunteers and supports woodworking, metal working, 3D printing, electronics prototyping, and crafting. Furthermore, its resources are open to individuals working on class assignments, research projects, or even personal use. While its hours of operation vary by semester, in general, it is open during weekdays, usually between 11 a.m. and 5 p.m. Because of its broad scope of technologies and openness to all Georgia Tech students, many of the modules were patterned after technologies available in this space.

Other spaces at Georgia Tech include the Interactive Product Design Lab (IPDL) in the School of Industrial Design, as well as the GVV Prototyping Lab in the School of Interactive Computing. Unlike the Invention Studio, however, these spaces host a limited number of tools and generally limit access to only students in particular programs or classes. An additional space that was created during the scope of this research was the Maker Closet which functioned as a specialized space for students taking courses in

which the maker modules were offered. This space provided additional resources and evening hours when students could receive help on class assignments or projects.

Much like Georgia Tech's Invention Studio, Berry College also has a centralized maker-oriented space called HackBerry Lab that is open to students and faculty. This space, however, is not as widely known across campus programs, and largely serves the Creative Technologies program, as well as some computer science, engineering, physics, and mathematics programs in a limited capacity. The lab is staffed by faculty and paid student lab assistants and is open to anyone during weekdays from 6 p.m. to midnight. Its resources are also available for class assignments, research projects, and personal projects. It supports a variety of prototyping technologies including woodworking, metal working, 3D printing, electronics prototyping, and crafting. Whereas the Invention Studio requires students to completely provide their own materials, HackBerry Lab has a variety of materials that students are free to use for their projects.

In terms of auxiliary spaces that support maker-oriented activities, Berry College is limited in its resources. While there are some spaces that offer very specialized types of fabrication capabilities, such as an on-campus welding shop, these spaces are generally very restricted with respect to access for students. One notable exception to this is the Physical Computing Lab which supports some maker-oriented activities during the semesters that a physical computing class is being offered (usually only in the spring).

*Table 17 – Characteristics of six facilities that support maker-oriented activities at Georgia Tech and Berry College.*

<b>Details</b>	<b>Invention Studio</b>	<b>GVU Prototyping Lab</b>	<b>Interactive Product Design Lab</b>	<b>Maker Closet</b>	<b>HackBerry Lab</b>	<b>Physical Computing Lab</b>
Institution	Georgia Tech	Georgia Tech	Georgia Tech	Georgia Tech	Berry College	Berry College
Availability	All Students and Faculty	Interactive Computing Students	Industrial Design Students	Maker-Module Students	All Students and Faculty	Physical Computing Students
Operating Hours	Weekdays 11am – 5pm	Hours Vary	Hours Vary	Tue/Thu 6pm-9pm	Weekdays 6pm-12am	Mon/Wed 8pm-11pm
Approximate Capacity	100+	15	24	6	50	15

*Table 18 – Maker-oriented activities supported by six facilities at Georgia Tech and Berry College.*

<b>Capability</b>	<b>Invention Studio</b>	<b>GVU Prototyping Lab</b>	<b>Interactive Product Design Lab</b>	<b>Maker Closet</b>	<b>HackBerry Lab</b>	<b>Physical Computing Lab</b>
Woodworking	X	X			X	X
Metal Working	X				X	X
Laser Cutting	X	X			X	
3D Printing	X	X	X		X	
Vinyl Cutting				X	X	
Electronics Prototyping	X	X	X	X	X	X
Electronics Production				X	X	
Crafting and Soft Goods	X		X	X	X	
Advanced CNC Tools	X	X			X	
Computer Stations	X		X		X	

Table 19 – Maker-oriented activities in relation to maker modules.

<b>Capability</b>	<b>Rapid Foam Board Prototyping</b>	<b>2D Design &amp; Fabrication</b>	<b>3D Printing &amp; Design</b>	<b>Wearable Technology</b>	<b>Prototyping with Arduino</b>	<b>Deconstruction of Technology</b>	<b>Working with Wood &amp; Metal</b>	<b>Circuit Design &amp; Soldering</b>
Woodworking							X	
Metal Working							X	
Laser Cutting		X						
3D Printing			X					
Vinyl Cutting		X						
Electronics Prototyping					X	X		
Electronics Production								X
Crafting and Soft Goods	X			X				
Advanced CNC Tools								X
Computer Stations		X	X		X			X

Understanding the capabilities of each maker-oriented space at the participating institutions was fundamental in creating the modules. Furthermore, it was important to consider how accessible the spaces were to the variety of students taking the courses and the availability of onsite assistance for students that were unfamiliar with the technologies. At Georgia Tech, these considerations led to modules that largely centered around technologies available at the Invention Studio and the Maker Closet. The Invention Studio provided the majority of support during the interventions. To accommodate this, in many of the courses, students were required to attend an orientation session and tour of the Invention Studio early in the semester to better acquaint themselves with the location, operating policies, and staff of the facility. Furthermore, of all the available maker-oriented facilities at Georgia Tech, it was able to handle the relatively large number of students that would be utilizing the space. In many cases, the Georgia Tech courses exceeded 50 students, which would have overwhelmed every other



on-campus location. Another benefit of this location was the presence of onsite student volunteers that were trained in the equipment and available to help students that had questions. There were, however, a few limitations associated with the Invention Studio. While the space was open to all students every weekday, its hours were limited to generally late morning to early evening, which some students found problematic with their class schedules. Furthermore, there were a few select capabilities that were not available at the Invention Studio, including access to a vinyl cutter and a source of electronic components. To supplement this, I developed a small space called the Maker Closet that would help address these limitations. The Maker Closet was a small, 250-square foot equipment closet where students could access additional resources for the courses. Access to the space was limited to only students and instructors in the maker module classes because of the limited space, and it was open during evening hours twice a week to accommodate students' class schedules. The largest function of the space was to provide students access to electronic components that were sourced for the activities and projects in the classes, as well as access to a vinyl cutter which was used in a few exercises conducted in the classes throughout the semester. Finally, the Maker Closet served as a resource for teaching assistants to meet with students and discuss class projects and explore how the maker-oriented technologies could assist in the development of that work. By focusing on the capabilities of the Invention Studio and supplementing them with resources from the Maker Closet, it was possible to develop and support the initial six maker modules that complemented the curriculum in the courses being studied.

At Berry College, a slightly different approach was implemented. Instead of holding the courses in a classroom separate from the maker-oriented facilities, they were conducted inside the maker-oriented facility: HackBerry Lab. While each of these approaches presented noteworthy challenges (to be discussed in Chapter 6), conducting the courses within HackBerry Lab eliminated the need to facilitate external orientations and trainings, as these could be incorporated directly into the course curriculum. Outside of normal class time, the space was open every weekday from 6 p.m. – midnight to accommodate students’ class schedules. Furthermore, the space was staffed with one or two student lab assistants who had previously completed the course and had additional training with the tools and technologies in the space. Because of the proximity to the technologies, it was possible to implement an additional two maker modules (traditional materials and circuit design) into the course curriculum.

## **5.2 Scaffolding Maker-Oriented Learning with Maker Modules**

For many students in the courses, physical prototyping was a relatively new activity that few had previous experience with. Because of this, it was important to consider how the maker-oriented learning activities could be scaffolded to support the learning goals associated with the course curriculum and remained topical and relevant to those objectives. Scaffolding can be a valid approach in HCI-centered courses, especially those that engage in problem- and project-based learning, as was the case in the courses studied at Georgia Tech and Berry College [15, 42, 63]. Barron emphasizes the importance of scaffolding in these types of learning environments because of the importance of creating

a balance between course concepts and tangible projects [15]. She describes this balance as being a struggle between a variety of potentially competing activities:

*“These included the balance between having students carry out design activities on the one hand and reflect on this work on the other, how to integrate students' real-world knowledge without letting it have too much influence over lesson plans, and how to maintain student engagement over an extended period of time in a way that pushes principled understanding rather than simply appealing to students' desire to tinker with their projects.” [15]*

To alleviate any potential conflict between these activities, it is important to consider how individual maker activities are structured, as discussed in Chapter 4, as well as which maker modules will best support the learning goals of the courses.

To illustrate how the selection of maker module topics can help scaffold students in their understanding of course learning goals, I will present an analysis of the Introduction to Prototyping course taught at Berry College. In this course, students learning outcomes are stated as the following:

1. *Human-Centered Design* - Students will understand a broad context of design thinking and human-centered design as it relates to the development of everyday technologies.

2. *Form and Function* - Students will understand the role between aesthetic forms and interactive functions and are able to express that role using appropriate concepts and terms.
3. *Problem Solving* - Students will demonstrate design distinctiveness and patient problem solving through developing technologies that address personally motivated contexts.
4. *Digital Fabrication* - Students will be able to demonstrate basic competency in using digital fabrication tools and technologies.

In preparation to introducing these maker modules into the Introduction to Prototyping course, these learning outcomes were considered and mapped against the available technologies at HackBerry Lab. In doing so, it was possible to examine how the modules would or would not support the course learning outcomes. In most cases, the maker modules were able to support two or more learning outcomes (Table 20). The one exception to this trend was the working with traditional materials (woodworking and metalworking) module. This module was not originally offered at Georgia Tech, but based on the proximity of woodworking and metalworking tools, in addition to the expressed interest of students taking this course, this module was introduced in the courses at Berry College. While the module only addresses the digital fabrication learning objective, it is a skill used by many students in the creation of course projects which do address the other three objectives and will be discussed in section 5.3.

*Table 20 – Relationship between maker modules and learning outcomes in Introduction to Prototyping course at Berry College.*

<b>Maker Module</b>	<b>Learning Outcomes</b>			
	Human-Centered Design	Form and Function	Problem Solving	Digital Fabrication
Rapid Foam Board Prototyping	X	X	X	
2D Design & Fabrication	X	X	X	X
3D Printing & Design		X	X	X
Wearable Technology	X	X	X	
Prototyping with Arduino			X	X
Deconstruction of Technology	X	X		
Working with Wood & Metal				X
Circuit Design & Soldering	X			X

This mapping resulted in the instructor being able to ensure that not only were the individual designs of the modules addressing specific learning outcomes, but also that the holistic collection of modules was addressing those outcomes equally. In fact, throughout this distribution of modules, each learning outcome is addressed by a combination of five of the eight available modules. In the following sections, I will discuss how each of these objectives is addressed in the modules with supporting examples and evidence.

### *5.2.1 Supporting Human-Centered Design through Maker Modules*

The most critical aspect of the Introduction to Prototyping course is to help students develop an understanding of human-centered design through the lens of common, everyday technologies. As students evaluate devices that they encounter in their lives, they can begin to understand the relationship between people and technology and explore a design-thinking process that serves to solve problems through the development of technologies that satisfy human needs.

In the Introduction to Prototyping course, this is achieved through three means. The first is through lectures and student reflections on human-centered technologies as

discussed in Don Norman's *The Design of Everyday Things*. This book lays a foundational understanding for students to be able to critically evaluate technologies that have been designed both well and poorly and gives them a context in which to understand how humans interact with devices [26].

The second means through which the course addresses this learning objective is through students developing two prototypes throughout the course of the semester. The first prototype, or intermediate project as it is called, is meant to engage students in a basic problem-solving exercise that allows them to demonstrate their understanding of human-centered principles. This is done through students identifying an interest or task that they are personally motivated by and developing a device that improves upon it. The second prototype, or final project, furthers this exercise by having the students either improve upon their first prototype, or to identify a new interest or task and repeat the process. The principle difference between the intermediate and final project, however, is that in the final project students must test their devices with a small sampling of users to gain additional feedback and insight into their ability to appropriately address human-centered needs through prototyping.

The third means through which students achieve this outcome is through the participation in the maker modules. While these modules directly address this outcome, they also serve as a scaffold for students to develop their understanding of both the lectures and readings, as well as the intermediate and final projects. Through the maker modules, students are able to explore and develop an understanding of topics such as affordances, signifiers, and discoverability—topics that are tangibly available to students during the modules. By providing this physical context for these topics, students are able

to confidently discuss the concepts when they later arise in class lectures and written reflections. Furthermore, the modules serve as a scaffold for students in the development of their intermediate and final projects. By participating in problem-based design challenges during the maker modules, students are able to explore human-centered design in a creatively constrained environment. Later, when they begin to develop personally motivated prototypes under more relaxed constraints, they are able to reflect on the lessons learned during the maker-oriented activities.

This learning objective is directly supported by five maker modules: Rapid Foam Board Prototyping, 2D Design and Fabrication, Wearable Technology, Deconstruction of Technology, and Circuit Design and Soldering.

#### 5.2.1.1 Rapid Foam Board Prototyping

In Rapid Foam Board Prototyping, students are challenged during the expansion section of the module to consider a variety of examples of interactive lamps that they have encountered. This could be anything from dimmable lights, light-sensitive night lights, motion-activated lights in a bathroom, or a stoplight. They then compare the purpose of these lights and how they are designed to fulfil a human-centered need. They then evaluate their selections on how well they are able to fill this need based on the critiques they participated in when presenting the interactive foam board lamps that they created during the maker module.

#### 5.2.1.2 2D Design and Fabrication

As part of the expansion step in 2D Design and Fabrication, students are given the task to develop an interface for a parking meter on a university campus. In doing so, they are able to consider how affordances and signifiers play a role in a human's ability to interact with devices. Through this exploration, they are also able to experiment with concepts such as accessible design for disabled users, cultural considerations for non-English speakers, and more. By experimenting with these constraints, students develop a context for discussing these topics as they appear in the lectures and projects.

#### 5.2.1.3 Wearable Technology

In the Wearable Technology module, students are able to learn and implement five human-centered design factors that must be considered when developing technology to be worn on the body. These factors include design considerations made based on the location of the device on the body, the activity being supported, the overall weight of the device, supporting natural human movement through design, size considerations based on device function, and designing for comfort and extended use. As part of the design exercise, students rapidly prototype a human-centered device that they must then user test with five other students. In doing so, they begin to understand how to evaluate their work based on simplified user testing and determine how well is has met the objectives outlined by the five human-designed factors.

#### 5.2.1.4 Deconstruction of Technology



In the Deconstruction of Technology module, students disassemble a user interface device such as a keyboard, mouse, or joystick, to understand the design decisions that designers and engineers make during the development of a human-centered technology. This experience provides students with an appreciation of how devices can be designed simply to address specific interactions without extraneous features. As part of the experience, students practice resource gathering and listing the user's desired actions that device must support. Afterward, students then disassemble the device to discover how these actions are made possible through the underlying technology. By doing so, they engage in a process that will be similar to the one they undergo when developing their own human-centered technologies.

#### 5.2.1.5 Circuit Design and Soldering

The last maker module to support the learning objective of design thinking and human-centered design is the Circuit Design and Soldering module. Throughout this module, students are challenged to consider how low-level hardware functions, such as buttons and indicator lights support human-centered concepts such as the mapping between inputs and outputs, or the visibility of system status. They discover and discuss basic usability heuristics that play into the user interface development topics covered in the course curriculum.

#### 5.2.2 *Supporting Form and Function Fluency through Maker Modules*

Frank Lloyd Wright, a prominent architect, designer and educator, was well known for saying that “form follows function—that has been misunderstood. Form and function

should be one, joined in a spiritual union” [26]. Thus, in the Introduction to Prototyping course, this principle of form and function working together to create a cohesive user experience is frequently emphasized. Furthermore, it is important for students to be able to describe the relationship between these concepts appropriately in order to understand how they influence each other’s role in the device.

This learning objective is consistently addressed through students working with technologies and fabrication methods that allow them to experiment with this relationship and justify design choices dictated by the demands of form and function. The modules that best address this objective include Rapid Foam Board Prototyping, 2D Design and Fabrication, 3D Printing and Design, Wearable Technology, and Deconstruction of Technology.

#### 5.2.2.1 Rapid Foam Board Prototyping

As part of the exposition step of the Rapid Foam Board prototyping module, students are asked to consider how the form and function of a simple light-sensitive night light complement each other. In doing so, students must contextualize the model of interactivity as it relates to inputs, processing, output, and physical form. In doing so, many students quickly realize how the form of the night light directly affects the function. As illustrated in section 4.2.1.2, the form of the night light prevents feedback errors through the strategic placement of the light sensor, in addition to the inclusion of a diffusion shield that scatters the lamp’s light. As part of this discussion, students are then invited to consider other devices that are designed in such a way that creates strong ties between form and function.

#### 5.2.2.2 2D Design and Fabrication

In this maker module, students learn the principles of 2D vector-based design in order to fabricate prototypes using laser cutters and vinyl cutters. In order to explore the relationship between form and function, groups of three students are given a small, random object during the *exploration* element of this module. They are instructed that they must design and fabricate a foam board enclosure for this object using the laser cutter. The faces of the enclosure must be interlocking and leave only a small margin of space between the edges of the enclosure and the object. In addition to this functional constraint, they must also create a graphic that must be laser-etched or vinyl-cut onto the enclosure. This graphic must conform to the form of the enclosure and must serve as a clue as to the identity of the object sealed inside the enclosure. At the end of the activity, students swap their creation with other groups and critique each other on how well the form and function of the enclosures matched the enclosed object.

#### 5.2.2.3 3D Printing and Design

In preparation for learning the principles of 3D printing and design, students interact with a 3D model of a horse leg. This model was developed in order to assist in the creation of a wearable device designed to perform gait analysis and lameness detection in horses. The origin of this model was the result of 3D scanning a horse and utilizing fabrication techniques that utilize the life-size form of the leg to assist in the functional development of prototypes. The motivation for this work was the difficulty in being able to develop wearable prototypes around difficult to access features (such as a

horse's leg). As part of this process, students are challenged to consider other design constraints where 3D printing and design would serve to help designers explore the relationship between form and function.

#### 5.2.2.4 Wearable Technology

After introducing the five factors of wearable technology design (as discussed in 5.2.1.3), students are invited to critique existing wearable technology devices and discuss how those five factors influence the form and function of these devices. For example, students discuss the form and function of an early prototype of Google Glass as well as a developed production model, in addition to a gesture-recognition device called Myo, and a handheld inventory scanner used by warehouse workers (Figure 8). Through the guided critique of these devices, students are able to establish the relationship between form and function as they related to wearable device concepts such as size, weight, location, comfort, and movement.



*Figure 8 – Students critique the form and function of wearable devices such as (left to right) an early Google Glass prototype, a production model of Google Glass, the Myo gesture recognition band, and a handheld inventory scanner.*

#### 5.2.2.5 Deconstruction of Technology

During the explanation step of the Deconstruction of Technology module, students are invited to present on their new-found understanding of the function of their devices and how those functions are supported through the device's form. For example, students will commonly comment on the form of keys on a keyboard and their ability to support repeated keystrokes that provide relative comfort to the user. Upon disassembling the keyboard, the students learn that this activity is made possible through a rubberized membrane that functions as a spring and provides useful feedback to the user. After this activity, they further this activity through the expansion step and brainstorm new devices that keep the same function as their original devices but explore new forms that would better suit their needs. Such expansions include students thinking about redesigning the form of a keyboard to better support playing competitive video games or adapting to users with disabilities.

#### 5.2.3 *Supporting Problem Solving through Maker Modules*

In a course such as Introduction to Prototyping where student projects are relatively open-ended, Barron contends that beginning with problem-based learning prior to engaging in projects can be an effective scaffolded approach [15]. He explains that focusing on problem solving early on creates opportunities for students to better engage with course content and helps establish student self-assessment through metacognition [15]. In the Introduction to Prototyping course, this self-assessment is critical because students are able to define their own problems in special interest areas where they may have access to knowledge resources unavailable to other students or instructors.

Furthermore, the course focuses on the concept of patient problem solving, a practice of allowing students to learn through experimentation and iteration [64]. This approach has been employed in STEM-focused classrooms where students are encouraged to consider real world problems that may have a variety of solutions [64, 65]. By using trial-and-error, students are able to evaluate early failures and use knowledge gained from experiments to motivate additional iterations of their work.

This approach is fundamental to student learning in the Introduction to Prototyping course and is reinforced through the maker-oriented approach in a variety of modules. These modules specifically focus on developing a problem-based design challenge where students are able to contextualize information from the exposition stage and experiment with it during the exploration stage. This approach is most prominently featured in the Rapid Foam Board Prototyping, 2D Design and Fabrication, 3D Printing and Design, Wearable Technology, and Interactive Prototyping with Arduino modules.

#### 5.2.3.1 Rapid Foam Board Prototyping

During the Rapid Foam Board Prototyping module, students are broken up into groups of three and given the challenge to design a lamp that addresses a specific problem that addresses some aspect of their lives as students. In doing so, students are motivated to develop lamp devices that are inspired from a personal interest or issue. In this exercise, the definition of lamp is established very broadly as any device that lights up, which gives students flexibility in regard solving a problem. Student ideas typically center around ideas such as lamps to help them wake up on time to get to class, athletic technologies that help prevent injuries or improve performance, or study aides such as

interactive desk lamps or bedside night lights for late night study sessions. By providing this design challenge to students early on in the semester, students are able to begin understanding how to identify problems and rapidly brainstorm and fabricate technologies that may address those issues. In a few cases, students have gone on to fully develop their lamp concepts later in the semester as an intermediate project for the course.

#### 5.2.3.2 2D Design and Fabrication

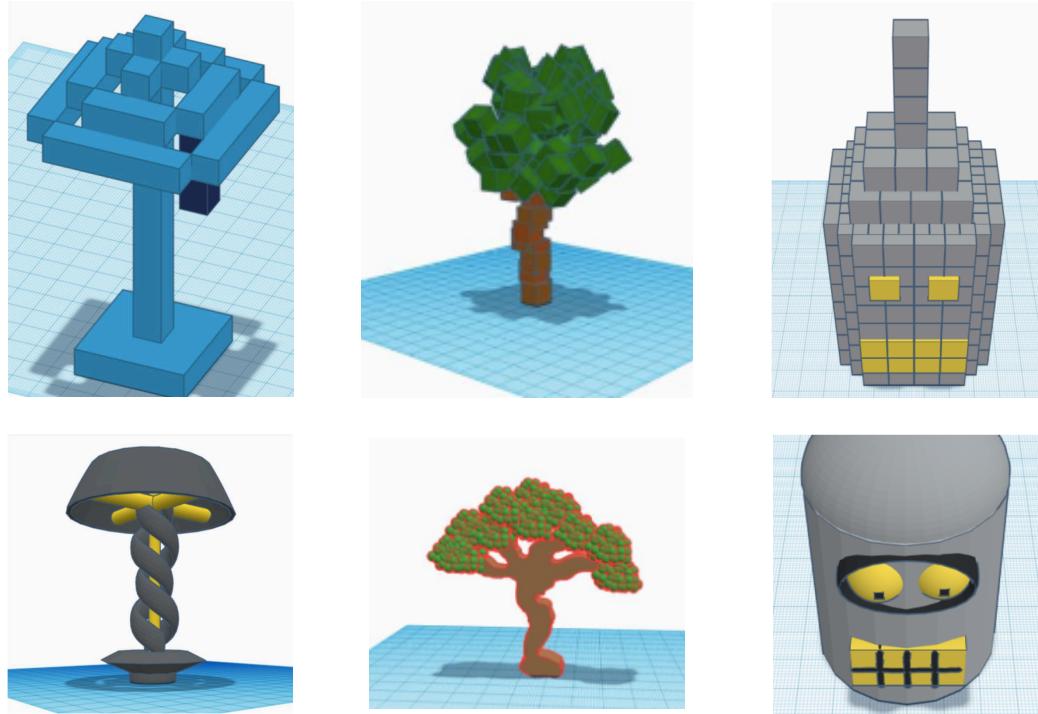
One of the most difficult aspects of physical prototyping is for students to establish a strong sense of scale when moving between virtual designs on computers, and tangible designs in the physical world. To help students become comfortable with this transition, they are assigned a specific design challenge during the expansion step of this module to create a customized name plate that conforms to certain criteria. The problem they are tasked with solving is getting to know one another during class exercises and presentations. To address this, they must create a laser cut and vinyl graphic-enhanced nameplate that meets specific design objectives such as maximum dimensions, legibility from a given distance, and the ability to stand upright and adhere to presentation surfaces such as magnetic whiteboards. Furthermore, students must personalize the nameplate in such a way where it expresses a personal interest or hobby that the student has. This technical challenge results in students developing a better sense of accuracy and detail in both their design acumen and fabrication skills, with many students iterating on their designs because of early failures. Most often these failures are associated with students overestimating the visibility of their nameplate from across a classroom. However,

through the iterative process of design, fabrication, evaluation, and reflection, students are able to develop a better sense of how early failures can lead to improved final results.

#### 5.2.3.3 3D Printing & Design

As the complexity of student designs increase, it becomes more important for them to be able to leverage tools that support the physical fabrication of such designs. The process of 3D design and printing, however, is oftentimes not intuitive because the design takes place in a simulated 3D space on a two-dimensional screen. This is not an unfamiliar frustration for students who often begin brainstorming larger projects and ideas by sketching on flat surfaces. Transforming these flat representations of ideas into tangible artifacts is not intrinsically easy. To address this, a two-step activity is used to introduce students to 3D design processes. The first step uses a simple 3D design software called Tinkercad, that allows students to develop complex geometries using simple primitive 3D solids, such as cubes, spheres, pyramids, and prisms [66]. Students are presented with a problem of needing to design a complex object such as a lamp, tree, or robot, but are only allowed to use congruent cubes measuring 10 millimeters in each dimension. This creative design constraint allows students of focus on learning the basic skills of geometric translations of objects, adjacency of components, and controlling camera viewpoints in a 3D space. During the explanation of the exercise, students are invited to consider common activities such as playing with Lego or Minecraft where relatively complex ideas can be manufactured from simple atomic shapes.





*Figure 9 – Example results of students designing objects using cubes (top row) and more complex objects (bottom row).*

After completing this preliminary exercise, students are then given the opportunity to recreate those shapes, however, now they are free to incorporate more complex geometries into their designs. The initial problem-based approach of the cube-based activity not only challenges the students to think abstractly about the primitive geometries of complex 3D objects, but also appropriately scaffolds the work in such a way that when they begin designing with more complex geometric primitives, they have an established workflow for translating, orienting, and viewing those designs in a 3D space.

#### 5.2.3.4 Wearable Technology

In the exploration of the Wearable Technology module, students are given the problem of developing a wearable device prototype that addresses a particular design need. Their prototypes must demonstrate elements of the five factors of wearable technology designed as described in 5.2.1.3. Specifically, their devices must do the following:

1. *Location on Body* – Students are assigned one of four regions of the body in which they must develop their prototype. These include the head, torso, arms, and legs. Students must identify an activity that could be supported by a wearable technology prototype on this region of the body and further localize it within that region, e.g. a wearable prototype for a leg may focus on monitoring a knee injury by being mounted in close proximity to the knee.
2. *Weight* – In order to simulate real life weights of devices, students must fabricate prototypes that weigh between 35 – 50 grams (this number was obtained by weight a variety of wearable technologies). Because students are using lightweight prototyping materials such as foam and moldable thermoplastic, they may embed small weights into their prototype to work their way up to this target weight.
3. *Comfort* – Students are encouraged to use ergonomic design to ensure their device is comfortable for their users. They are also instructed to make their devices adjustable, where possible, in order to suit a variety of body types. They are given the guidelines that devices must not fall off the user when

bending over to pick keys off of the ground, and it should not be so restrictive that it would be uncomfortable for the user.

4. *Movement* – Students must create devices that can support movement in the activity being studied. To test this, students must demonstrate that their devices will not impair a user from performing jumping jacks.
5. *Size* – This design constraint has the largest amount of variability because of the number of areas for which a student may design their device. For example, the size of a back-mounted posture sensor may differ drastically in scale from a finger-mounted pulse sensor. Students are advised that the final size of the prototype should be reasonable with relation to the part of the body they are designing for.

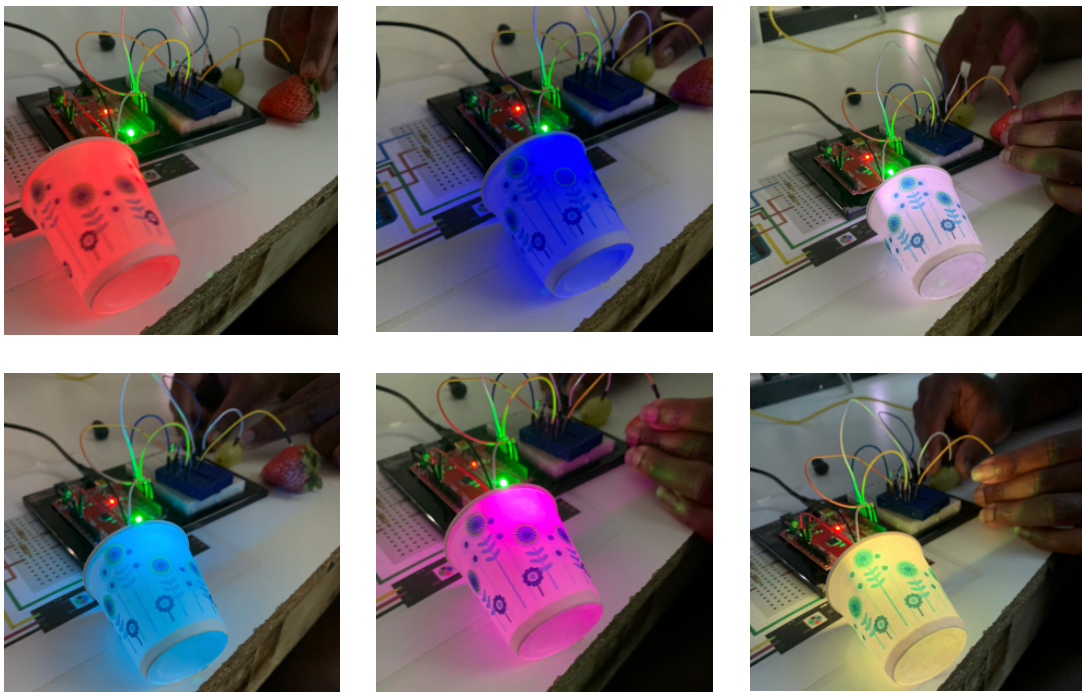
Throughout this activity, students are actively engaged in problem solving as they develop a context for their device within the constraints of the assigned area of the body. Furthermore, a large amount of iteration generally occurs within the designated time for the design challenge, as well as afterward during an informal user testing session where students critique each other on how well their prototypes exhibit the properties of the five design factors. During the design sessions, the most frequent iterations are made to the devices weight, with students checking the weight of their devices on scales and either adding or subtracting weight from their devices to get it within the acceptable range. During user testing, students most often iterate within the comfort criteria as they test the adaptability of their device with a variety of body types.

#### 5.2.3.5 Interactive Prototyping with Arduino

During the exploration step of the Interactive Prototyping with Arduino, students are given the problem of developing an interactive model that helps demonstrate the principles of the visible light spectrum and color theory. In this maker module, students develop a non-traditional interface using fruit to represent the primary colors of lights, i.e. strawberries for red, grapes for green, and blueberries for blue. Through the creation of this project they develop fundamental skills necessary for working within the constraints of both the software development environment, as well as the hardware and circuit design. Students work from a provided sample circuit schematic but must work with group members to extrapolate that example to interact with the three-color sensors. Furthermore, they are supplied with sample code that provides low level access to the incoming sensor values and an addressable RGB LED that is capable of producing a full spectrum of colors. Their task is then to develop a model that receives incoming values from the sensors and appropriately thresholds those values individually. Because the sensors rely on capacitive touch sensing, incoming sensor values will vary dramatically relative to the size and moisture content of the fruit that has been attached to the sensor. Students must then develop a mathematical model that takes incoming values which can range from zero to over 5,000 and map them to acceptable RGB values which must range between zero and 255 (Table 21). This process is highly iterative as students take into account small variations in sensor values and creating an interface that is appropriately reactive to human interaction. Finally, students are given a set of ten colors that they must produce using the color primitives of red, green, and blue. They are then instructed to further adjust their color models to fine tune the system to display these colors.

*Table 21 – Sample mathematical color model developed by students to map incoming touch sensors to RGB LED.*

Target Color	Incoming Sensor Values			Outgoing LED Values		
	<i>Strawberry</i>	<i>Grape</i>	<i>Blueberry</i>	<i>Red</i>	<i>Green</i>	<i>Blue</i>
Red	1022	8	2	255	0	0
Green	11	988	3	0	255	0
Blue	12	5	721	0	0	255
Yellow	450	953	0	128	255	0
Orange	1120	612	8	255	128	0
Cyan	9	981	735	0	255	255
Purple	512	2	708	128	0	255
Pink	1075	5	723	255	0	255
White	1098	955	698	255	255	255
Black	10	9	6	0	0	0



*Figure 10 – Examples of students creating different light colors through combinations of inputs from a capacitive touch sensor.*

### *5.2.4 Supporting Digital Fabrication through Maker Modules*

The last learning objective for Introduction to Prototyping states that students should be able to demonstrate basic competency in using digital fabrication tools and technologies. Not only is this a primary component of a maker-oriented learning approach as outlined by this work, but creating tangible artifacts through digital fabrication can contribute to understanding by creating additional contexts and touchpoints through which students can reference course concepts [42]. As such, achieving a level of competence with the digital fabrication tools and methods is a learning goal in itself. While each module touches upon various fabrication methods, this particular learning goal acutely focuses on those that allow students to transfer abstract knowledge into digital designs that can be rapidly iterated upon and shared, and then transform those digital representations into tangible artifacts through technologies popularized by the maker movement. These modules include 2D Design and Fabrication, 3D Printing and Design, Interactive Prototyping with Arduino, Working with Traditional Materials (Wood and Metal), and Circuit Design and Soldering.

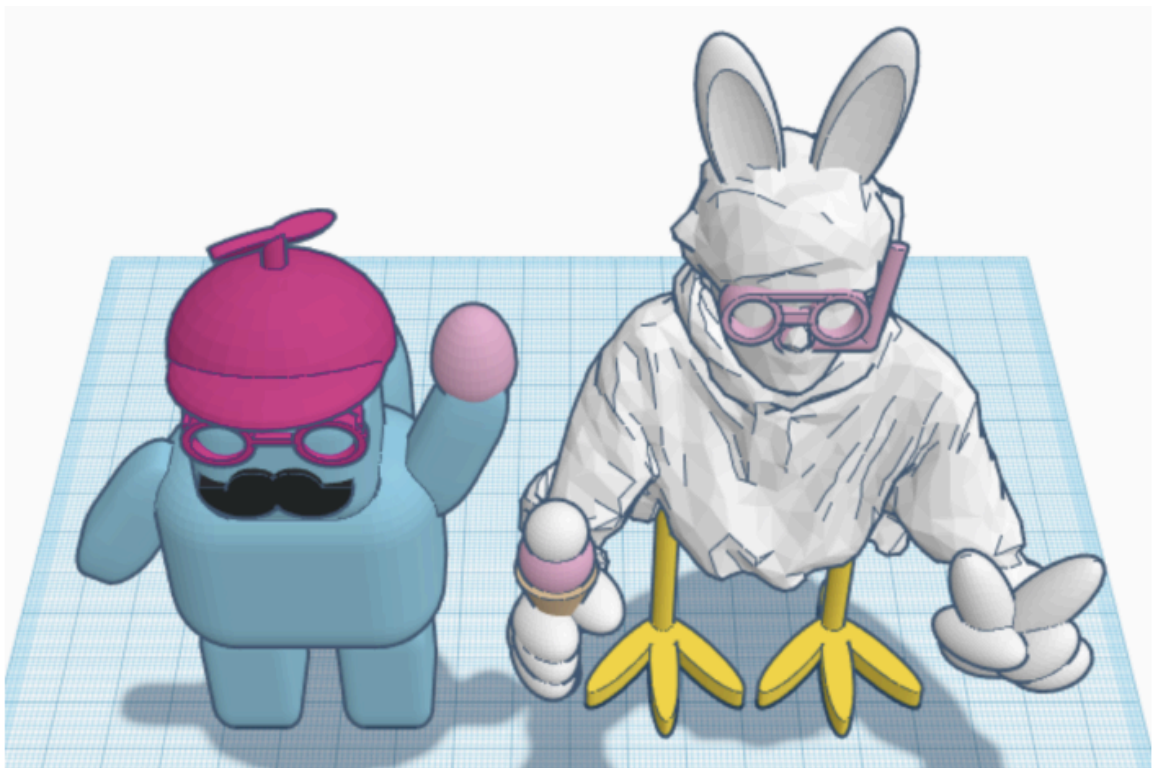
#### 5.2.4.1 2D Design and Fabrication

One of the main objectives of the 2D Design and Fabrication module is to familiarize students with the operations of both software and hardware in the production of physical prototypes. Students use a series of technologies that allow them to transition between digital concepts to tangible designs in a logical fashion. During the exploration stage of this module, students participate in requirements gathering to create an enclosure for an object. This includes considering the shape and form of the object as well as the

dimensions. Using Inkscape, a free vector-based graphics program, students are able to design simple shapes that can be interpreted as toolpaths for CNC machines. In the first part of this exercise, they design the faces of an enclosure that interlock such that the assigned object will fit inside compactly. Students then export this file in a laser cutter-compatible format that will command the laser to follow a predetermined path for cutting the enclosure out of foam board. Students are then able to test, adjust, and recut their enclosures as necessary. This iterative process is useful for students as it provides them an opportunity to explore manufacturing tolerances when enclosure designs are either too small or too big. Furthermore, they also become familiar with the balance that the laser power intensity and the cutting speed play into achieving consistent cutting results. While it is possible to generalize these power and speed settings, the specific setting used will vary depending on the work, thus students gain insight into these nuances through their repeated work. After creating the enclosure, students then create graphics that are inspired from the object being stored inside. This graphic is often times generated using existing imagery from the internet, and students employ a process of bitmap tracing which uses various image processing algorithms to turn a bitmap (pixel) image into a vector (path) image. Much like the power and speed iterations that students must experiment with, the results of bitmap tracing also vary depending on the source image. Experimenting with tracing settings further familiarizes students with the Inkscape software and allows them to see how the algorithm affects the results through a preview window.

#### 5.2.4.2 3D Printing and Design

In the 3D Printing and Design module, students are given the opportunity to create a unique artifact using a combination of 3D technologies. While students work on the exploration step of this module (creating designs using complex 3D primitive shapes), the instructor uses an Xbox Kinect to 3D scan each student using the Skanect open source software. This 3D design file is made available to students who then modify the design in the Tinkercad 3D software to augment their bodies in some creative way (Figure 11).



*Figure 11 – Example of an augmented 3D scan in Tinkercad.*

Upon completion of this design, students then use a 3D printer to fabricate their design. One of the significant challenges students face during this process is in



experimenting with various printer settings to achieve a satisfactory print. This includes balancing the demands of quality versus time and infill percentages versus structural integrity. In regard to quality and time, students must choose a layer thickness for their print. In 3D printing, successive layers of thermoplastic are laid down to create solid objects. The thicker these layers are, the faster the print can be completed, but this comes at the cost of a lower resolution print since the individual layers are visible. Students must experiment with these settings in order to achieve a balance between the two extremes of a very low-quality print versus a print that takes many hours to complete. Finally, students must explore the properties of infill to determine the structural properties of their prints. In many cases, 3D printers only fill in a small portion of the interior of the print. It is common for printers to print with a 20 percent infill where 80 percent of the interior of the print is empty space. The percentage of infill, however, has a direct relationship to the structural integrity of the piece. As such, students must consider the final application of their prints and adjust the infill accordingly to conserve filament where possible.

#### 5.2.4.3 Interactive Prototyping with Arduino

Physical computing with Arduino and other microcontrollers is a helpful resource for teaching programming and electronics principles in classroom settings [38, 67]. For many students in the Introduction to Prototyping course, this is their first interaction with any type of programming or circuit building. With that in mind, a very scaffolded approach is taken that helps students iteratively build on small programming and circuit design exercises. This is achieved progressively through both the exposition and exploration steps of the maker module framework. In the exposition step, students

construct two simple circuits to establish the fundamental operations of the Arduino development environment. The first circuit, Blink LED, has the students attach a single LED to the board and write a few lines of code that cause the LED to blink at a steady rate. Students then learn the basics of creating an electronic circuit as well as how to create data structures, establish connectivity, and handle program control with a small set of commands. After successfully making the LED blink at a steady rate, students are then invited to gradually increase changing the speed of blinking through adapting the code until the LED is no longer discernibly blinking and instead appears to be constantly lit (this usually occurs around 12 milliseconds between blinking operations). A small discussion is then held that refers back to previous class discussions and determining whether or not this circuit conforms to the model of interactivity—most agree that it does not because it lacks a discrete input sensor. To remedy this, students then construct a second circuit, Button LED, which adds a simple push button to the circuit. In doing so, students learn about inputs, conditional statements, and monitoring microcontroller processes through a serial port window. The benefit of this activity is that it simply augments upon the previous concepts and allows students to immediately refer to knowledge gained in the preceding activity. As seen in Table 22, the exploration activity, Rainbow Fruit, is the culmination of concepts learned during the first two exercises (with the exception of the `DigitalWrite` command) and adds a few additional functions for students to expand upon. At the conclusion of these exercises, students have been able to practice basic programming and circuitry skills three times using a hands-on approach to understanding the principles of interactivity and prototyping electronic circuits.

*Table 22 – Table of scaffolded programming and electronics concepts covered in the Interactive Prototyping with Arduino maker module.*

<b>Task</b>	<b>Type</b>	<b>Blink LED</b>	<b>Button LED</b>	<b>Rainbow Fruit</b>
LED Basics and Polarity	Hardware	X	X	X
Resistor Functions	Hardware	X	X	X
Digital Outputs	Hardware	X	X	X
Setup and Loop Functions	Software	X	X	X
Declare Variables	Software	X	X	X
PinMode Input Command	Software	X	X	X
DigitalWrite Command	Software	X	X	
Delay Command	Software	X	X	X
Buttons and Voltage Dividers	Hardware		X	X
Pull Up and Pull Down Resistors	Hardware		X	X
Digital Inputs	Hardware		X	X
PinMode Output Command	Software		X	X
DigitalRead Command	Software		X	X
Serial Communication	Software		X	X
Conditional Statements	Software		X	X
Addressable LEDs	Hardware			X
Capacitive Touch Sensors	Hardware			X
Software Libraries	Software			X
Analog Inputs	Software			X
Analog Outputs	Software			X
Thresholding Functions	Software			X
Mapping Functions	Software			X

#### 5.2.4.4 Working with Wood and Metal

While the Working with Traditional Materials module predominantly deals with shaping and joining metal and wood through the use of non-digital fabrication tools, such as saws and drills, the expansion step for this module has students explore basic CNC tools, such as a CNC wood router. For this activity, students refer back to the experience gained during the 2D Design and Fabrication module and create a vector-based graphic that can be transformed into tool paths for the CNC router to etch a design into a piece of wood. Through this, students can leverage another touchpoint with working through the process of translating a digital design into a tangible artifact. Prior to etching the wood, students run a design simulation using a path generating tool called Easel that allows

them to double check their designs for errors prior to running the tool. The final scope of their work is constrained to a 10 x 10-inch workspace, which allows them enough workroom to develop intricate designs, but not so much room that design failures result in hours of lost work. As such, this module instructs students in a variety of fabrication methods available for working with wood and metal – both digital and non-digital.

#### 5.2.4.5 Circuit Design and Soldering

The last maker module that supports students in being able to leverage digital fabrication tools in the creation of physical prototypes in the Circuit Design and Soldering module. In this module, students explore the principles of printed circuit boards (PCBs) through a warmup activity of examining a simple LED-embedded keychain (Figure 12). Students are then introduced to EasyEDA, an online electronic schematic and PCB design tool. Students are then challenged to create a simple interactive LED keychain using the design features observed during the warmup activity. They begin by creating an electronic schematic that symbolically models the electrical connections between the components. Afterward, they translate this schematic into a PCB that challenges them to consider the physical constraints of arranging and connecting those components onto a circuit board. Finally, students fabricate this board either through the use of an CNC circuit router, such as the Cirquid, or have the board printed by a manufacturer. After the board is created, they are then able to solder the LEDs, resistors, battery, and switch to the board.

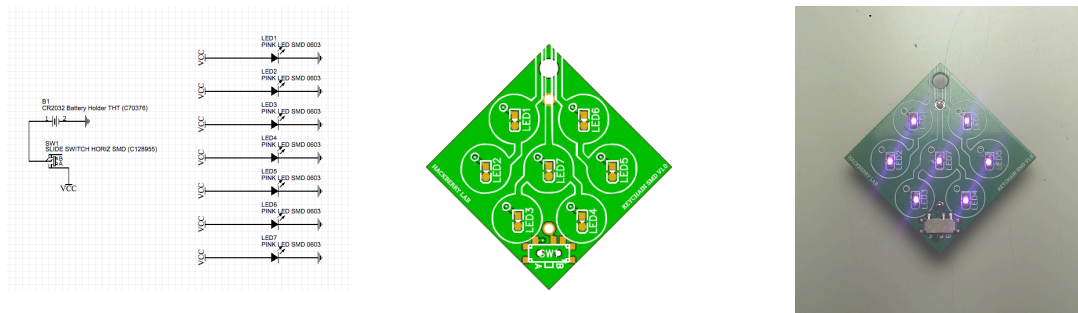


Figure 12 – Circuit design and fabrication process in three steps (left to right): electronic schematic design, PCB design, and final soldering and assembly.

### 5.2.5 Maker Modules Scaffolding Maker Modules

In addition to the maker modules scaffolding the overall course objectives for the Introduction to Prototyping course, it was also important to consider how the modules were able to scaffold each other. As I iterated upon the order in which the modules were presented, it was important to consider how work completed in earlier modules would affect the student experience and learning in modules taught later (Table 23).

Table 23 – List of maker modules that scaffold other maker modules in the Introduction to Prototyping course taught at Berry College.

Foundation Module	Advanced Module	Scaffolded Principle
Rapid Foam Board Prototyping	2D Design and Fabrication	Understanding the principles of foam board and creating physical prototypes from flat materials.
Rapid Foam Board Prototyping	Wearable Technology	Working with foam board and basic hand tools to rapidly create physical prototypes.
Rapid Foam Board Prototyping	Prototyping with Arduino	Developing a model of interactivity to describe inputs and outputs.
2D Design and Fabrication	3D Design and Fabrication	Creating 3D objects using geometric primitives.
2D Design and Fabrication	Working with Wood and Metal	Generating CNC toolpaths using vector-based design software.
Prototyping with Arduino	Deconstruction of Technology	Understanding the principles of basic electronic circuits to define device functionality.
Prototyping with Arduino	Circuit Design and Soldering	Understanding electronic schematics and principles of components to create printed circuit boards.

One of the advantages of structuring the modules this way was that it allowed students to build from past experiences with the concepts and techniques learned in previous modules. Furthermore, it provided them with another touchpoint in engaging with the hands-on tools to develop a basic competence in the function and safe operation of those tools. Finally, the ability to build upon previous modules created efficiencies in administering the class because it was possible to consolidate the tools and materials required for conducting the variety of maker modules.

### **5.3 Supporting Student Work through Iterative Development of the Order of Maker Modules**

Just as the various elements of the maker module framework were iteratively developed through the process described in Chapter 4, the overall structure and order of the maker modules changed over time to support student work being done in the Introduction to Prototyping course. These iterations were largely undertaken as a result of the analysis of three main influences. These include the optimization of the order of maker modules to capitalize on opportunities to scaffold learning through shared skills and concepts (as discussed in section 5.2.5), student feedback provided through course evaluations and surveys, and a technology requirements study conducted on the intermediate and final projects created by students in the course.

In preparation for each semester, data from the previous semester was gathered, analyzed, and used as a starting point to create the order of modules as shown in Table 24. In addition to considering the order in which the modules were offered, it was also important to factor in which weeks the modules would be conducted. This timing was

determined by significant class events, such as when students began and completed class projects, school holidays, and guest lectures.

The initial order of the modules in the Introduction to Prototyping class was largely based on the order which had been implemented in the spring 2015 Mobile and Ubiquitous Computing course offered at Georgia Tech. Two additional modules were included (Circuits Design and Soldering, and Advanced 2-Dimensional Fabrication) to take advantage of additional technologies available to the students through HackBerry Lab. The timing of the modules was spread evenly among the first 12 weeks of the course, with three modules being taught during each of the first three quarters of the semester. No modules were scheduled to be taught during the last week of the third quarter or any time during the fourth quarter. This was done with the assumption that students would use those weeks to complete work on the final project. This initial ordering created some challenges, both with practical implementation by the instructor, as well as some deficiencies when it considering the projects students created for both the intermediate and final projects in the course. After initially observing these difficulties, it was decided to iterate upon the order and timing of the modules to more efficiently accommodate the instruction and to better support the student projects.

*Table 24 – Evolution of maker module order taught in Introduction to Prototyping course at Berry College. Light grey areas show intermediate project timeline and dark grey areas show final project timeline.*

Class	1 <sup>st</sup> Quarter				2nd Quarter				3rd Quarter				4th Quarter			
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
F15	DT	RP		WT	3D 3F		2D 2F	WW	AF	CS	AR					
S16	RP	2D 2F	3D 3F	WT		WW MW	CS			AR	DT	AF				
F16	RP	3D 3F	2D 2F	WT	MW WW	AR				DT	CS	AF				
S17	RP	3F	2D 2F		3D	WT	WW MW	AR	DT		CS	AF				
F17	RP	3D		2D 2F	3F	WT	AR	WW	MW	DT	CS	AF				
S18	RP		3D	2D 2F	3F	WT	AR	WW	MW		DT	CS	AF			

*Table 25 – Maker module topic abbreviations.*

Abbreviation	Maker Module
RP	Rapid Foam Board Prototyping
2D	2-Dimensional Design
2F	2-Dimensional Fabrication
3D	3-Dimensional Design
3F	3-Dimensional Fabrication
WT	Wearable Technology Prototyping
AR	Interactive Prototyping with Arduino
WW	Woodworking
MW	Metal Working
DT	Deconstruction of Technology
CS	Circuit Design and Soldering
AF	Advanced 2-Dimensional Fabrication

### *5.3.1 Spring 2016 Modifications to Maker Module Order and Timing*

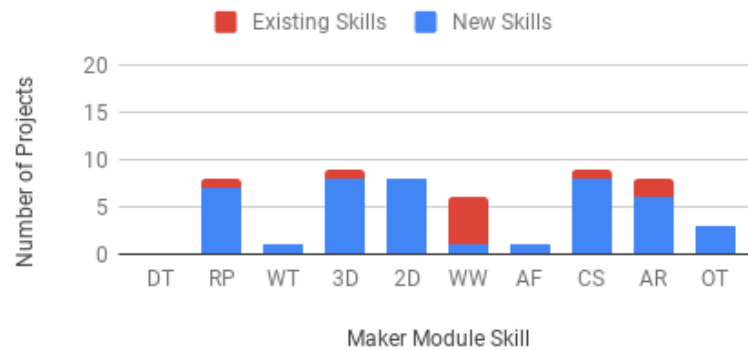
At the completion of the Fall 2015 offering of Introduction to Prototyping (ITP-F15), five significant changes to the order and timing of the modules were undertaken as a result of evaluating data collected during that semester. The first significant change was to move the Deconstruction of Technology module from the first quarter (Q1) to later in



the third quarter (Q3). This activity was originally meant to encourage students to explore existing handheld technologies in order to evaluate the form and function of the devices. It was also thought that some students could implement deconstructed devices into their course projects either through modifying them or salvaging parts from them. At the conclusion of ITP-F15 it was concluded that students' abilities to perform the evaluations were not satisfactory. Observationally, students had a difficult time balancing the task of working with small electronic components while also trying to critique the devices using specific language introduced into the class during the first week of the semester. Thus, for ITP-S16, this activity was relocated to Q3 and the Rapid Foam Board Prototyping Activity took its place during the first week of exercises. In this exercise, students create a simple paper prototype of an interactive lamp of their own design. Because the form and function of these prototypes is constrained by both the material and the design challenge, students were better able to complete the task and use appropriate terminology during the critique session. It was also observed that the Deconstruction of Technology module had little or no influence in students' course projects during ITP-F15.

### ITP-F15 Intermediate Project Technology Usage

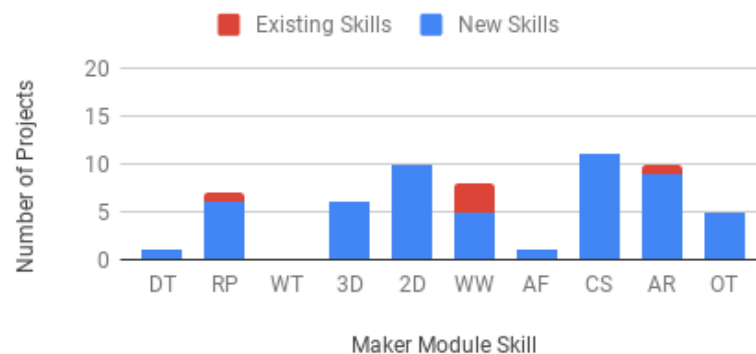
n = 17 projects



*Figure 13 – Technology usage in intermediate projects among students in the Fall 2015 Introduction to Prototyping course.*

### ITP-F15 Final Project Technology Usage

n = 17 projects



*Figure 14 – Technology usage in final projects among students in the Fall 2015 Introduction to Prototyping course.*

In Figure 13 and Figure 14, it can be seen that among the 34 total projects created that semester, only one project implemented a deconstructed device. While this module still served a valuable purpose in helping students explore how both aesthetics and interactive functions influence everyday technologies, it was evident that other modules, such as the

Rapid Form Board Prototyping could scaffold students' learning to better prepare them for the Deconstruction of Technology module.

The next significant change implemented in ITP-S16 was to move the 3D Printing and Design module and 2D Design and Fabrication module to significantly earlier in the semester. During ITP-F15 these modules were not taught until Q2, with the 3D module being taught during week 5, and 2D being taught during week 7. This presented a significant challenge to students that wanted to implement these technologies into their intermediate projects that semester. Development on intermediate projects start fairly quickly in the Introduction to Prototyping course to allow students significant time to complete their projects. In ITP-F15, students worked between weeks 2 and 8 on intermediate projects as seen in Table 24. Of the 17 intermediate projects created during this class, 9 of them used 3D technologies and 8 used 2D technologies, with only one student having any previous 3D experience, per Figure 13. Because of this, students spent a significant amount of time out of class receiving additional help from the instructor during open lab hours. To alleviate this strain, it was decided to significantly accelerate the timeline in which the 3D and 2D modules were offered. As such, in ITP-S16 the modules were moved to Q1 with the 2D module being taught during week 2 and the 3D module being taught during week 3. Furthermore, student development on intermediate projects was delayed until week 3 to give students additional time to consider the technologies that would be covered in class to allow them to more appropriately scope their work.

The last significant change to the ordering of the maker modules during this time was in considering the timing of the Advanced 2D Fabrication module. This module is

generally not included among the other modules because of the unique set of technology requirements that it demands. In the Advanced 2D Fabrication module, students learn about more sophisticated CNC fabrication tools such as a circuit mill and CNC router. While these tools are more fully explored in more advanced Creative Technologies classes, their purpose in the Introduction to Prototyping course is more informational than experiential. As such, this module does not conform closely to the maker module framework outlined in Chapter 4 and is not included in the list of formal modules. The informational role of this module became apparent during ITP-F15 when it was observed that the level of skill required by students to understand and operate these tools would require more time than could be allotted in the course. Furthermore, the time required per student to make a project with each of these tools was prohibitively lengthy. Whereas a single project on a laser cutter may take five minutes at most, a circuit fabricated on the circuit mill may easily take an hour or more. One way to overcome this would be to employ several mills, as is the case with having multiple 3D printers for students to concurrently run time consuming jobs. However, unlike the relatively inexpensive 3D printers, the high cost of circuit mills makes this approach infeasible. These considerations made it apparent that this module would be best reserved until the end of the semester. This allowed it to appropriately foreshadow technologies that would be explored in successive classes and not delay other modules that could be more applicable in ongoing project work.

### 5.3.2 Fall 2016 Modifications to Maker Module Order and Timing

In preparation for the ITP-F16, it became apparent that the timing of the Interactive Prototyping with Arduino and the Traditional Materials (Woodworking and Metal working) modules needed to be adjusted. This was motivated by feedback received from the course evaluation surveys submitted by students, as well as from an analysis of the technologies utilized in the intermediate and final projects. When prompted to reflect on the relationship between course instruction and projects, students responded as such:

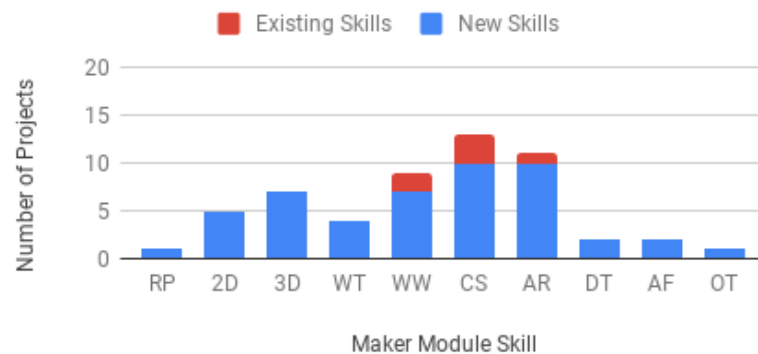
*I think some of the skills that would be useful for the intermediate and final projects might be better earlier in the semester, like woodworking and electronics. (ITP-S16)*

*By the time we had the woodworking class, many of us had already learned those tools for a project. (ITP-S16)*

This indicated that there was a disconnect between student expectations of when these technologies would be introduced with respect to when students were trying to implement them into the course projects. This feedback corroborated data gathered from technologies used during course projects as well. In Figure 15 and Figure 16, it can be seen that out of 38 total projects, 22 used the Arduino microcontroller and 18 used woodworking or metal working technologies.

### ITP-S16 Intermediate Project Technology Usage

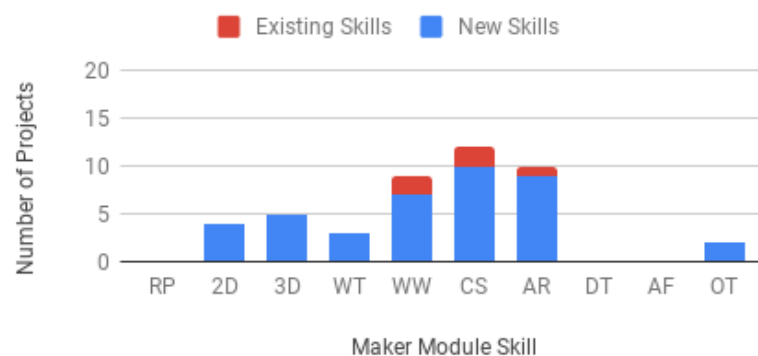
n = 19 projects



*Figure 15 – Technology usage in intermediate projects among students in the Spring 2016 Introduction to Prototyping course.*

### ITP-S16 Final Project Technology Usage

n = 19 projects



*Figure 16 – Technology usage in final projects among students in the Spring 2016 Introduction to Prototyping course.*

During ITP-S16, the Traditional Materials module was taught during week 6 in Q2 and the Arduino module was taught during week 10 in Q3. This would be moved to week 5 and week 6 in Q2 for the Traditional Materials and Arduino modules respectively, giving

students an additional three to four weeks to incorporate these modules into their intermediate projects.

### *5.3.3 Spring 2017 Modifications to Maker Module Order and Timing*

The changes made to the spring 2017 offering of Introduction to Prototyping were largely prompted by external influences on the course. Between the fall 2016 and spring 2017 offerings, the 3D software that was traditionally used (Sketchup) significantly changed its usage model, severely limiting the software functions available to those that were using the free version. This prompted a change in the course to use a browser-based 3D design program by Autodesk called Tinkercad. With this new software came some opportunities to support more advanced 3D design topics such as 3D scanning and modifying existing 3D files as a result of the software's enhanced file import capabilities. In order to accommodate this additional functionality, it was decided to spread the 3D Printing and Design module across two class sessions. This would allow for increased time for students to explore the 3D software capabilities. Furthermore, this also allowed adequate time in the 3D printing portion of the module for students to not only observe a 3D printing demonstration, but also allowed them to interact with the 3D printers to fabricate their own small design within the class session.

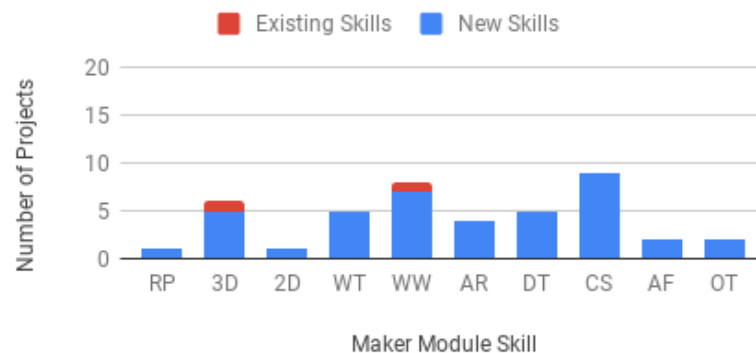
### *5.3.4 Fall 2017 Modifications to Maker Module Order and Timing*

The last few significant changes to the overall maker module order emerged from the growing trend of students using the Arduino microcontroller in their projects. This, in some part, is contributed to the restructuring of earlier modules to focus on interactivity,

which in turn increased students' propensity to embed interactive electronics into their work. In addition to this upward trend, it was also observed that a significant number of students were incorporating elements of the Traditional Materials module into their work. While these two trends were noted during ITP-S16, in this iteration it became apparent that students may benefit from reversing the order of these modules. While both would still be offered during Q2, it was decided that the Arduino module would be taught first because a portion of students using traditional materials were entering into the class with existing skills in working with traditional materials.

#### ITP-S17 Intermediate Project Technology Usage

n = 22 projects

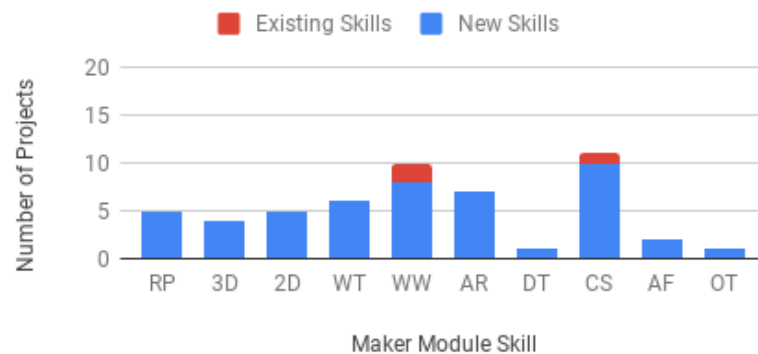


*Figure 17 – Technology usage in intermediate projects among students in the Spring 2017 Introduction to Prototyping course.*



## ITP-S17 Final Project Technology Usage

n = 22 projects



*Figure 18 – Technology usage in final projects among students in the Spring 2017 Introduction to Prototyping course.*

Furthermore, an additional change was made to the Traditional Materials module in order to better support student learning and safety. Before ITP-F17, the Traditional Materials module combined both woodworking and metal working into a single class session. This resulted in students feeling rushed to complete the in-class exercises, as well as the instructor being able to monitor only one of the spaces where work was taking place. These circumstances presented some safety concerns, as well as a challenge to students being able to focus on their work and make connections to overall course concepts. To address these concerns, this module was split into two sessions – one in-class session where students could work with woodworking technologies and individualized out-of-class sessions where students were able to develop skills with metal working technologies. As a result of this change, it was observed that students were better able to produce artifacts in both sessions that represented the learning objectives of the class.

### 5.3.5 *Emerging Patterns in Maker Module Order and Timing*

Throughout the iterative development of the ordering and timing of the maker modules within the six offerings of Introduction to Prototyping, some emerging patterns manifested that can help structure the maker module curriculum.

The first pattern is that of practical implementation of the modules. In the case of dividing the 3D Printing and Design module and the Traditional Materials module, some topics have a broad scope that makes covering the required material in one class session unfavorable. Class session length, tool usage, and other factors that influence practical implementation are discussed in greater detail in Chapter 6.

The next pattern that emerged is reactive module structuring. In this, the instructor can adjust the order and timing of modules based on reactions to previous implementations of the course to better anticipate instruction required to support student projects. In this, it became important to triangulate data gathered through observations, student evaluations, and the technology usage studies. By considering this data, instructors are better able to anticipate what technologies will be used predominately in the development of student projects and adjust the order and timing of supplementary modules appropriately. This approach, however, does have limitations as it is not always predictable what previous experiences students will be entering the class with. This is especially true because the Introduction to Prototyping course is generally taught as a freshman course with no prerequisites, so there is no guarantee that students have had previous experience with any technologies. Throughout the six courses studied 66% of students ( $n = 126$ ) reported no previous experience with any of the technologies covered

in the maker modules. Among the students with previous experience, the most prominent skills include traditional materials (22%), 3D printing and design (9.5%), and circuits and soldering (8.7%) as seen in

Table 27.

*Table 26 – Number of skills with which students enter Introduction to Prototyping.*

Number of Skills	% Students
0	65.9%
1	24.6%
2	7.1%
3	0.8%
4	0.8%
5	0%
6	0.8%
7	0%
8	0%

*Table 27 – Ranked skills with which students enter Introduction to Prototyping.*

Skill	% Students
Traditional Materials	22.2%
3D Printing & Design	9.5%
Circuits & Soldering	8.7%
Arduino	5.6%
2D Design & Fabrication	1.6%
Deconstruction of Technology	1.6%
Paper Prototyping	0%
Wearable Technology	0%

Another pattern that emerged is when the instructor makes prescriptive decisions regarding the order and timing of the modules in order to influence students to consider a diversity of technologies in their projects. Among the courses included in this study, students use between 2 to 3 different technologies in the creations of their projects. The mean number of technologies used in a project is  $2.75 \pm 0.26$  ( $n = 126$ ,  $p = 0.001$ ). In many cases, this is because some technologies logically pair with each other, for example

the Arduino module and Circuit Design and Soldering module will often times go together when students are developing moderately complex circuits. Similarly, paper prototyping and 2D fabrication often share resources such as foam board. As such, it can be prudent for an instructor to order the modules in a way that helps students make these natural connections between modules and implement them appropriately into their projects. Another result of this prescriptive approach is in helping students engage with unfamiliar prototyping technologies. Among intermediate and final projects, students used an average of  $3.26 \pm 0.25$  new technologies in the course ( $n = 126$ ,  $p = 0.001$ ). This figure excludes projects in which students used skills they had acquired previous to this course. This means that the average student uses nearly half of the available technology skills taught in the class in their projects.

#### **5.4 Developing New Modules to Address Emerging Technologies in Student Work**

Because of the open-ended nature of the projects created in Introduction to Prototyping, there were several instances of students implementing technologies that were not covered by the maker modules (Table 28). While it was not observed that any of these individually represents a significant influence in the total of all projects created, it does create a data point that can be considered for future module creation and implementation. For example, as discussed in section 5.3.1, I implemented an experimental module called Advanced 2D Fabrication that posed significant challenges to being implemented into the structure of the course and was relatively unused in student projects because of those challenges.

Table 28 – Other technologies used during student projects in Introduction to Prototyping.

Skill	Projects
Mold Making	7
Processing	6
Raspberry Pi	5
Mobile App Development	4
123D Make	3

Among the 126 projects created during these courses, the technologies from the Advanced 2D Fabrication module were only used 16 times. When compared to technologies used in projects that were not discussed in class such as mold making, Processing (a Java-based programming language), and Raspberry Pi (a small form factor computer), it may be reasonable to consider developing a module that could potentially replace the Advanced 2D Fabrication module. In doing so, it would follow the pattern of reactive module modeling, as it would be responding to the types of technologies students are trying to implement into their projects.

## 5.5 Discussion

Throughout this chapter, a number of contributions were made while answering the question “*What does a holistic curriculum of maker modules consist of?*” They included guides to assessing technology resources on university campuses, methods for scaffolding maker-oriented learning with maker modules, as well as an approach to iterate both the content of the maker modules as well as the order they are delivered to better support student work.

Several resources were developed to assess technology resources on a university campus and evaluate how they can support classroom-based maker-oriented activities. These resources include how to evaluate facilities on campus through their availability to

the broad range of students that are in human-computer interaction courses, particularly with respect to student access restrictions, operational times, and overall capacity of these facilities. Furthermore, this section described how to correlate technology requirements from maker modules to the available resources on campus.

After establishing a method for evaluating campus resources, an example of connecting course learning objectives to each of the maker modules was shown in detail to demonstrate how modules can be developed and adapted to reinforce a course's curriculum. This example is furthered in discussing how both the content and order of the modules evolved over time in response to students' capabilities and demands in their project-based work. An additional outcome of studying the several iterations of this course also led to the development of additional modules which signify another contribution, as well as a list of topics that could be developed into modules that would further assist students' work.

## **5.6 Conclusion**

In answering the question “*What does a holistic curriculum of maker modules consist of?*”, three significant concepts were explored that have broad implications for instructors that are implementing maker-oriented activities into their courses. The first is a method through which they can evaluate the technology resources available to them through campus facilities. Understanding the technology constraints is a fundamental step for these instructors because access to these facilities and technologies can sometimes be ambiguous. Thus, through using the resources outlined in the first section of this work,

instructors can understand the specific constraints of their individual campus' and adjust their activities accordingly.

The second concept developed is a method for specifically correlating specific course learning objectives to the physical activities within maker-modules. This was demonstrated through a case study of the Introduction to Prototyping course, which utilizes several learning objectives common among human-computer interaction courses. This case-study further outlines an approach which an instructor can evaluate the appropriateness of the prescribed modules in work to their own courses, as well as how they may develop new courses to fit learning objectives that are unique to their curriculum.

The last concept explored in this chapter focused on how the project-based learning students engage in throughout these courses can be affected by the order in which the modules are taught. This order was influenced by both the types of projects students were developing to address the overall requirements of the course, as well as how to structure modules in such a way that skills learned early on in the semester could be applied and reinforced in modules that occurred later. This section should be of great interest to instructors that anticipate that many of their students may be unfamiliar with maker-oriented learning or maker-inspired technologies, as the order in which modules are offered, as detailed in this work, can greatly affect how skills and concepts are scaffolded throughout the course. Furthermore, the application of the methods used to order modules in this chapter may also serve to help instructors themselves develop the confidence and skills necessary to the implement such activities into their courses.

## **CHAPTER 6. PRACTICAL IMPLEMENTATIONS FOR MAKER MODULES**

Throughout the development of these maker modules, a number of practical considerations had to be made in order to make implementing such activities into university classrooms practical. Therefore, in this chapter I will answer the final research question: *What considerations and practices are necessary when implementing maker modules in a traditional classroom and curriculum?* Implementing problem-based challenges into traditional HCI courses can present a number of practical challenges such as reduced time for lecturing, access to appropriate physical facilities, and managing tools and materials for a variety of class sizes [68, 69]. Any difficulty in one of these area can present a significant roadblock to the implementation of these maker-oriented learning strategies [70]. Therefore, I will address the practices that were developed in this work to address these common issues and provide guidelines that can be utilized by instructors that may implement maker modules into their curriculum.

### **6.1 Structuring Class Session Time for Maker Modules**

One of the primary concerns in deploying maker modules into class sessions was with respect to the amount of class time the modules would take. It was important that the modules contribute substantially to the overall learning goals of the course to justify the time taken away from traditional classroom activities such as lecturing, as discussed in section 5.2. However, it was also important to consider how to structure the length of



activities to allow for adequate time for students to fully achieve the objectives of each module. In order to accommodate the time needed for activities, the length of each course was experimented with to determine what would best fit the maker module approach.

*Table 29 – Scheduling and class session lengths among courses implementing maker modules.*

<b>Semester Year</b>	<b>Institution</b>	<b>Course</b>	<b>Days</b>	<b>Time</b>	<b>Session Length</b>	<b>Weekly Hours</b>
Spring 2015	Georgia Tech	Mobile & Ubiquitous Comp	Th	3 – 6 p.m.	3 hours	3 hours
Fall 2015	Georgia Tech	Prototyping Interactive Systems	M	9 a.m. – 12 p.m.	3 hours	3 hours
Fall 2015	Berry College	Introduction to Prototyping	MWF	3 – 4:30 p.m. (Class) 3 – 5 p.m. (Lab)	1.5 hours (Class) 2 hours (Lab)	4 hours
Fall 2015	Georgia Tech	User Interface Design	MWF	2 – 3 p.m.	1 hour	3 hours
Spring 2016	Georgia Tech	Mobile & Ubiquitous Comp	MW	6 – 7:30 p.m.	1.5 hours	3 hours
Spring 2016	Berry College	Introduction to Prototyping	TTh	3 – 5 p.m.	2 hours	4 hours
Fall 2016	Georgia Tech	User Interface Design	MWF	2 – 3 p.m.	1 hour	3 hours
Fall 2016	Berry College	Introduction to Prototyping	TTh	3 – 5 p.m.	2 hours	4 hours
Spring 2017	Berry College	Introduction to Prototyping	TTh	3 – 5 p.m.	2 hours	4 hours
Fall 2017	Berry College	Introduction to Prototyping	MW	1 – 3 p.m.	2 hours	4 hours
Spring 2018	Berry College	Introduction to Prototyping	MW	1 – 3 p.m.	2 hours	4 hours

Balancing time between lecture and maker modules proved to be difficult in early iterations of this study. The first iteration, MUC-S15, took a unique approach and met once a week for three hours, allowing the instructor to present both lecture and maker module activities within the same class session. While it is not always possible to schedule a class in this manner, there were some distinct advantages to being able to present the material in this timeframe. In interviews, students responded favorably when asked about the balance between lecture and maker module activities, with many

commenting on how the maker modules enriched the lecture portion of the class. For example:

*Lecture would have been boring if there had not been these activities, so I think the two together were good. But if it had been just one or the other it would not have been good. (MUC-S15)*

*For me the activity portion is the biggest piece. There is a lecture component, but that isn't necessarily the core focus of the class. The lecture was there to help aide in the activity, so the activities tend to really reinforce what we're learning. (MUC-S15)*

*I really liked that it was different. I feel like it actually made you think and work, which was nice. The emphasis on the hands-on activities and the group activities, especially at the beginning where it was split between lecture and group activity...and just actually having you do things and work, rather than just talking about it. (MUC-S15)*

It was also interesting to see how the inclusion of the maker modules in conjunction with the lectures created an increased expectation among the students to be responsible for the material covered in class. Some students expressed that they felt more compelled to listen and participate during class because they knew that they would be required to use the concepts discussed during the in-class activities:

*I probably would have paid less attention in this class if it had been just a lecturer speaking. So, because of the all the in-class activities, I was forced to participate and forced to at least know something about the project in order to contribute to the conversations that were going on. (MUC-S15)*

It was not possible, however, to always schedule courses in this once-a-week, three-hour meeting format. In the first iteration of the Introduction to Prototyping course, the class met three times per week, with two one-hour sessions dedicated to lecture, and one two-hour session dedicated to maker module activities. This approach was less successful when compared to the longer format explored in the MUC-S15 course offering. Students responded that the disconnect between concepts discussed during the lecture days and practiced during the module days made the course less structured. Furthermore, the shorter lecture days seemed to be inadequate for covering all the necessary concepts in order to appropriately prepare students for the maker module days:

*The discussion days often felt rushed, so spacing out the discussion time with the hands on time would better create a sense of structure and stability. (ITP-F15)*

*The only thing that I think could be improved was the amount of time that things were covered. (ITP-F15)*

As additional courses were offered and iterated upon, most courses settled on meeting twice a week for 90 or 120 minutes per class session. This seemed to alleviate student concerns regarding the amount of time required to cover the necessary concepts and still allowed a practical amount of time in which to conduct the maker modules. When asked how this course structure compared to other classes, one Georgia Tech student responded:

*This is a lot better. I felt more engaged, even during the lecture portions, because of the fact that we actually got to implement the ideas, versus like just listening to a professor talk to us for an hour and a half. (MUC-S16)*

In most cases, courses were structured around first presenting course concepts through lectures that would lead into maker-oriented activities. However, in early offerings, this order was occasionally reversed for external reasons. This reversed order did seem to have an effect on some students. Because of the active participation, and sometimes physical efforts required by the maker modules, students commented that when the maker-modules were taught first, then followed by lecture, that their desire to participate was lower:

*I liked lecture in the beginning, then the activity in the end. In some classes, he would do lecture in the beginning and then an activity at the end. Then other classes, he would do the activity in the beginning and lecture at the end. So,*

*towards the end of those classes most people are tired and are like, “I don’t really want to answer questions.” (MUC-S15)*

Thus, upon future iterations, when lecture and maker modules were presented consecutively in the same class, the instructor was encouraged to trend toward saving the maker module activities for the end of class.

The amount of time required for each module was subject to ongoing development as well. As the role of the maker modules grew in each of the course offerings, and as each semester brought a variety of course scheduling challenges, it was important to develop flexibility within each of the modules to allow them to suit a variety of class time constraints. As seen in Table 32, the timing of each element in the maker module framework can be adjusted to adapt the overall time required in a class session. In the exposition element for example, the amount of time required can be adjusted through the inclusion or exclusion of case studies and examples discussed, which in most cases can add or subtract around 10 minutes from the overall class. During the exploration element, however, efficiencies can be made by adjusting the amount of time given to students during the timed design challenges that often make up the bulk of activity during this portion of the maker module. One important consideration to make when doing this, however, is to adjust expectations of the quality of work when less time has been allotted. For example, in the Rapid Foam Board Prototyping module, the instructor can limit the number of ideas generated by students during the initial brainstorming session. During longer sessions, each student in a group of three is required to generate three unique ideas (for a total of nine ideas generated by the group). In truncated sessions, however, this

number is reduced to only three ideas generated by the entire group in total. Furthermore, the amount of detail expected in the foam board prototypes should be adjusted in accordance to the overall amount of build time given to students. The time required during the explanation element is very elastic as well. In courses that have a large number of students or very strict time constraints, explanations can be reduced to quick 10 or 30-second “elevator pitches” where students have a very brief amount of time to justify their work with respect to the module objectives and requirements. Where more time is allotted or in the case of smaller courses where the number of presentations is fewer, students can be given additional time to present, as well as have time to receive instructor feedback and peer critique from other students in the class. In some cases, such as the 2D Design and Fabrication, 3D Printing and Fabrication, and Traditional Materials modules, the expansion element is required to be completed outside of class because of the larger amount of time required by the other elements in these modules.

*Table 30 – General time allotments for maker module framework elements.*

Module	Maker Module Framework Element					Total Time
	Expectation	Exposition	Exploration	Explanation	Expansion	
RP	10 min.	20 – 30 min.	25 – 40 min.	10 – 20 min.	10 min.	75 – 110 min.
2D/2F	5 min.	30 – 40 min.	45 – 60 min.	5 – 10 min.	<i>Out of Class</i>	85 – 115 min.
3D/3F	5 min.	30 – 45 min.	30 – 45 min.	10 min.	<i>Out of Class</i>	85 – 115 min.
WT	10 min.	30 min.	25 – 45 min.	10 – 15 min.	10 – 15 min.	85 – 115 min.
AR	5 – 10 min.	15 – 25 min.	45 – 60 min.	15 min.	10 min.	90 – 120 min.
WW/MW	5 – 10 min.	20 min.	45 min.	20 – 30 min.	<i>Out of Class</i>	90 – 105 min.
DT	5 – 10 min.	15 – 20 min.	30 – 45 min.	15 – 20 min.	10 min.	75 – 105 min.
CS	5 – 10 min.	15 – 25 min.	45 – 60 min.	10 min.	5 – 10 min.	80 – 115 min.

One result from analyzing the amount of time that can be allotted to each framework element in the maker modules is an understanding of how elastic some modules are compared to others. For example, the Traditional Materials module that

addresses woodworking and metal working is relatively inelastic with little allotted variance among framework elements. There is only a total variance of 15 minutes between the shortest and longest version of this module. This is largely a result of the amount of time required to cover safety protocols and making sure that students are not rushing through various portions of the module. Thus, the exposition and exploration elements are concretely set regardless of the allotted class time. This inelasticity is one of the contributing factors for this module only being included in the Introduction to Prototyping course where there was a greater amount of control over course scheduling and structure. More elastic modules, such as Rapid Foam Board Prototyping and the Circuits and Soldering, allow for a greater variance and thus flexibility in timing structure. Each module has a difference of 35 minutes of variance between short and long versions with the Rapid Foam Board Prototyping module taking between 75 and 110 minutes and the Circuit and Soldering module taking between 80 and 115 minutes. This makes these modules extremely adaptable for a wide variety of course structures, and can often accommodate an additional classroom exercise, such as discussing a previous homework assignment, during the same class period.

One significant limitation of the modules, however, is their incompatibility with traditional one-hour (or 50-minute) class offerings. A subset of maker modules was conducted during the User Interface Design courses at Georgia Tech (UID-F15 and UID-F16) and each posed significant challenges with respect to conducting each element within the framework. During these offerings, the expansion element was eliminated completely, and warm up exercises during exploration elements were reduced to instructor-led demonstrations to keep the class moving along.

Table 31 –Allotments for maker module framework elements in UID-F15 and UID-F16.

Module	Maker Module Framework Element					Total Time
	Expectation	Exposition	Exploration	Explanation	Expansion	
RP	5 min.	15 min.	20 min.	10 min.	<i>Not Conducted</i>	50 min.
WT	5 min.	15 min.	25 min.	5 min.	<i>Not Conducted</i>	50 min.
DT	5 min.	10 min.	20 min.	15 min.	<i>Not Conducted</i>	50 min.

While presenting all of this material posed significant challenges for the instructors, a similar frustration was felt among the participating students as well.

*Timing for some of the activities felt like an issue. For example, the foam board one was fine, and it was fun, but another activity, I missed the first two minutes and I immediately felt like I was out of the loop. There were so many things going on that I felt like it would be better if we had more time and it had been broken down a little more. (UID-F15)*

*Some of them were kind of frustrating, particularly the one where we did wearable prototypes, just because of the time constraint thing. A lot of people didn't really get to do nearly all of what it looked like. (UID-F16)*

Because of these constraints, further iterations of the modules were only presented in 90- or 120-minute class sessions to prevent issues associated with being able to provide an adequate amount of time for instructors to cover the necessary material and for students to complete the required activities.



## 6.2 Physical Space Considerations to Accommodate Maker Modules

Throughout the production of maker modules, a variety of physical considerations were taken in order to enable instructors to deliver the content and support students while working on the hands-on activities. As seen in Table 32, five different classroom spaces were used to conduct the maker module sessions, each posing a variety of opportunities and challenges that will help administrators and instructors to determine how they may implement these modules into existing infrastructure or purpose-built spaces. These considerations span a variety of classroom characteristics including the physical classroom space and typical usage, artful surfaces for capturing information within the space, as well as accessibility and proximity to electrical power and maker-oriented equipment.

*Table 32 – Scheduling and class session lengths among courses implementing maker modules.*

Semester/Year	Institution	Course	Location
Spring 2015	Georgia Tech	Mobile & Ubiquitous Comp	Clough 102
Fall 2015	Georgia Tech	User Interface Design	Clough 102
Fall 2015	Georgia Tech	Prototyping Interactive Systems	Whitaker 1214
Fall 2015	Berry College	Introduction to Prototyping	Green 203 / Physical Computing Lab
Spring 2016	Georgia Tech	Mobile & Ubiquitous Comp	Clough 102
Spring 2016	Berry College	Introduction to Prototyping	Physical Computing Lab / HackBerry Lab
Fall 2016	Georgia Tech	User Interface Design	Clough 102
Fall 2016	Berry College	Introduction to Prototyping	HackBerry Lab
Spring 2017	Berry College	Introduction to Prototyping	HackBerry Lab
Fall 2017	Berry College	Introduction to Prototyping	HackBerry Lab
Spring 2018	Berry College	Introduction to Prototyping	HackBerry Lab

### 6.2.1 Classroom Space and Layout

The physical classroom space had an enormous impact on how the maker modules were structured and conducted. Characteristics such as maximum occupancy, dedicated or general purpose use, and classroom furniture, affected the delivery and

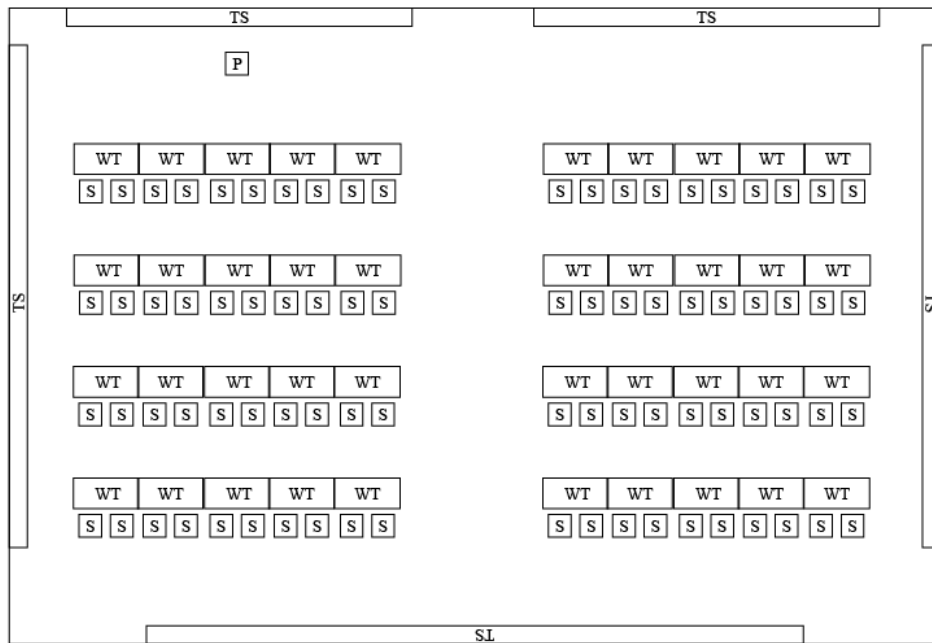
results of the modules. In this section, we will examine each physical space based on these features and detail the actions taken to accommodate the maker modules given those considerations.

#### 6.2.1.1 Clough 102 - Georgia Tech

Clough 102 is a somewhat unique learning space located in the Clough Undergraduate Learning Commons at Georgia Tech. While the space is often used a general purpose classroom, meaning that each day a variety of typical lecture-style courses are taught in it, the classroom does have some special features that accommodated maker-oriented learning activities well. These features came as a result of the Classroom 2000 project, which sought to improve the student learning experience by embedding lecture-capture equipment into the space [71]. With respect to capacity, this space was one of the largest used for the modules and accommodated up to 80 students in a single class session. Because the most common use case for the classroom was general lecture, the class was most often configured with tables and chairs arranged such that all attention was directed to the front of the classroom where the presentation equipment was located (Figure 19).

*Table 33 – Schematic abbreviations and descriptions of room features in classroom schematics.*

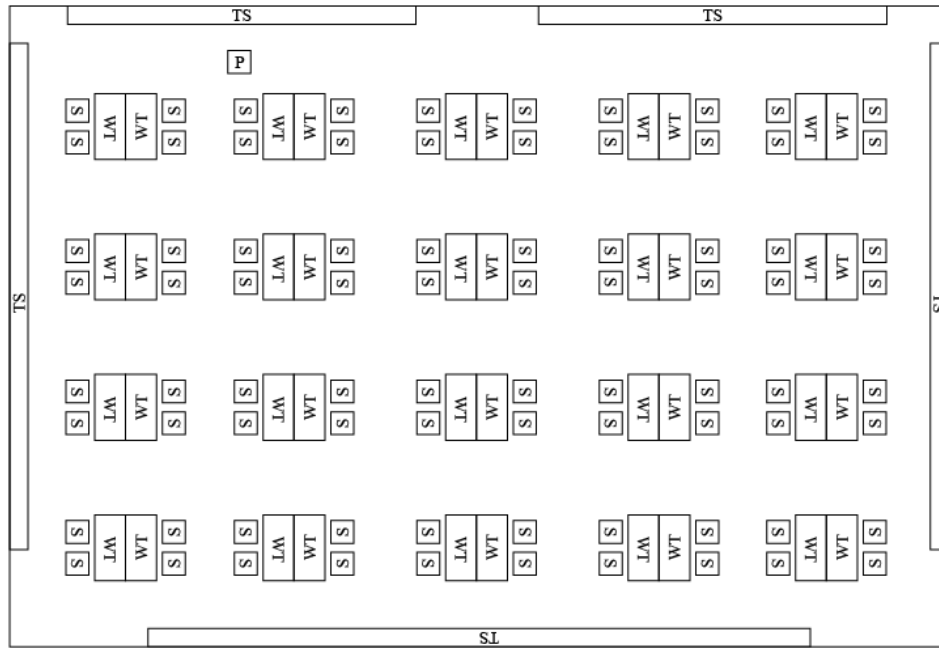
Abbreviation	Room Feature	Feature Description
P	Presenter Location	Usually a desk or lectern with presentation technology such as a computer, projector, or overhead camera.
S	Student Location	Student location with chair or stool.
TS	Artful Surface	Surfaces such as projection screens, dry erase boards, of pinup boards.
WT	Worktable	Standard desk height work surfaces for students.
LT	Lab Table	Raised work surfaces for students.
E&S	Equipment & Storage	Additional space for equipment and material storage.



*Figure 19 – Typical room layout of Clough 102 classroom space at Georgia Tech.*

For the purposes of the maker modules, this traditional configuration would be cumbersome because it does not easily support students working in groups with more than two people and created narrow aisles that limited students' ability to get up and move around. However, one unique feature of this classroom was that the tables and chairs were all equipped with rollers that made moving each piece of furniture fairly easy. On days in which maker modules were being presented in class, the instructors would rearrange the classroom as seen in Figure 20. This configuration still allowed students to see the projection surfaces at the front of the classroom, but also supported collaborative work as they were arranged in groups of four. Furthermore, the combining

of tables along the long edges created a more versatile workspace that allowed larger materials to be used in the modules. The redistribution of tables and chairs also had the desirable effect of making it easier for students to get up and move around the classroom without having to narrowly pass by others. This provided students better access to the dry erase boards along the walls of the classroom as well as to materials located on tables around the space. It also provided better access to instructors and teaching assistants to visit each group to monitor progress and offer assistance during the modules.



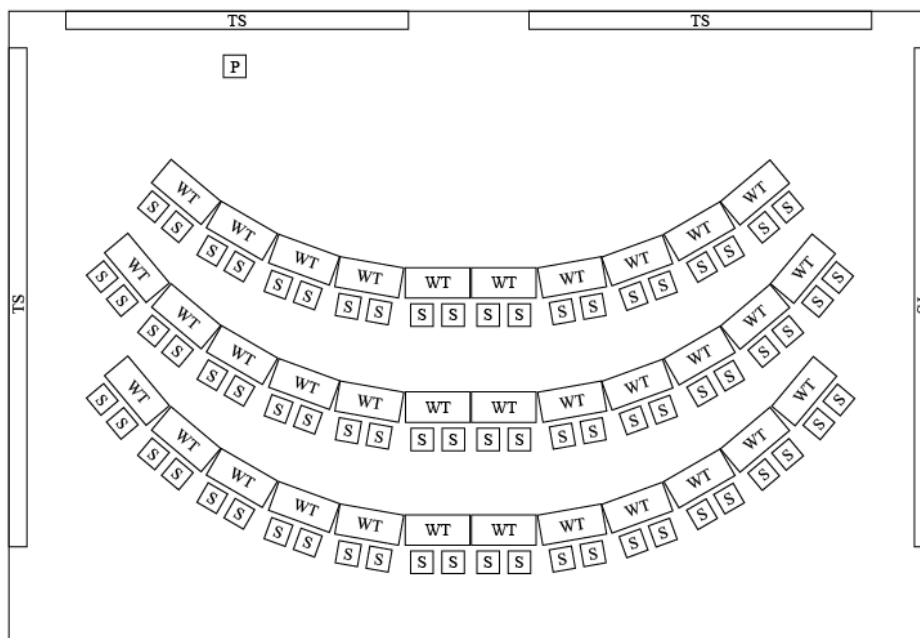
*Figure 20 – Adjusted layout of Clough 102 classroom space to accommodate maker modules at Georgia Tech.*

One of the most significant drawbacks to this arrangement, however, was that the process of moving the tables and chairs had to occur before and after each class session. This was because it was necessary to restore the traditional configuration in order to

accommodate the other courses that were taking place in the classroom that day. This became particularly difficult when classes were meeting directly before and after the maker module sessions, leaving fewer than 10 minutes to transform the classroom without cutting into instructional time.

#### 6.2.1.2 Whitaker 1214 - Georgia Tech

Because of scheduling difficulties during the Georgia Tech maker-module courses, one of the five treatments was taught in Whitaker 1214, which posed significant challenges and me to test the maker modules in a more constrained space.



*Figure 21 – Typical room layout of Whitaker 1214 at Georgia Tech.*

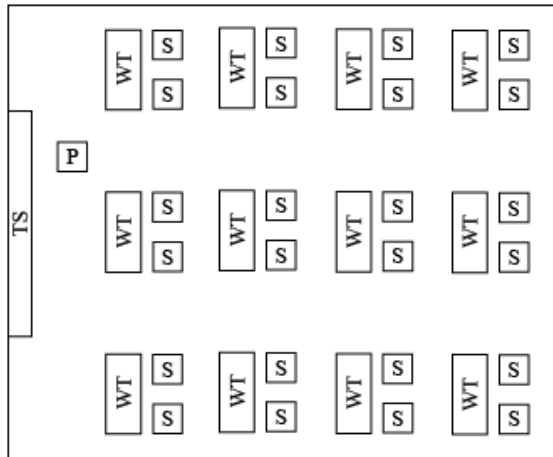
As seen in Figure 21, the Whitaker classroom seated a similar number of students as Clough (68 students); however, this classroom was structured as a tiered auditorium with immovable tables. This made coordinating and organizing group activities difficult and limited the mobility of students when trying to access tools and materials. Because of the large classroom capacity, it was still important to have students work in groups, and so a hybridized group strategy was developed for this classroom. For some of the maker modules that used minimal materials or tools, it was possible to create groups of three students, resulting in around 22 groups. This allowed students to sit side-by-side and still have a reasonable amount of interaction with each other. Modules such as the Rapid Foam Board Prototyping, 2D Design and Fabrication, 3D Printing and Design seemed to work efficiently using this grouping method. For the Wearable Technology, Interactive Prototyping with Arduino, and Deconstruction of Technology modules that used a broader range of tools and materials, it became necessary to organize students in groups of four. To accomplish this, two students in one row would work with the two students in the row directly behind them. The tiered nature of the classroom made this approach unideal because it often resulted in students needing to stand for the duration of class in order to be able to meaningfully interact with their group members. Furthermore, it became important for instructors to provide traditional kits of materials (as opposed to workbench kits) to groups because the lack of student mobility made it difficult for students to access some parts of the classroom without interrupting other groups. Finally, the narrow aisle access made it difficult for instructors and teaching assistants to monitor and help groups in the center of the classroom.



*Figure 22 – A visual comparison shows the tiered seating of an auditorium-style classroom (left) versus flat seating in a traditional classroom such as Clough 102 (right).*

#### 6.2.1.3 Green 203 - Berry College

In addition to the very large class sessions conducted at Georgia Tech, a number of similarly-structured courses were taught at Berry College as part of its Creative Technologies program. As this program was structured within the Campbell School of Business, the first sessions took place in Green Hall, the business school's primary academic building. The first course taught as part of this study was conducted with 17 students in a traditional lecture-style classroom. The classroom itself had a capacity of 24 students, typically arranged with two students to a table. The classroom was designed for lecture-based instruction with various classes meeting in it each day. One of the major limitations to this space with the relative immobility of furniture. The tables in this classroom were heavy and immovable and the chairs neither rolled nor swiveled. As such, it was deemed impractical to rearrange and reset the furniture before and after each class session.



*Figure 23 – Typical room layout of Green 203 classroom space at Berry College.*

When maker modules were conducted in this space, a hybridized approach was used that was similar to that in the Whitaker classroom. Modules that used fewer tools or materials were constrained to groups of two students, and more resource intensive modules had students work with other students in the rows behind them. This latter approach, however, was undesirable because the narrow tables made it quite difficult for four students to work at the same space. Given these difficulties, the space was abandoned in the middle of the semester and an alternative space was allocated where the modules could be conducted. This alternative space was the Physical Computing Lab at Berry College.

#### 6.2.1.4 Physical Computing Lab - Berry College

For latter part of the Fall 2015 course offering in which modules were conducted, the Physical Computing Lab at Berry College was used as an alternative space to overcome some of the limitations of Green 203. It was also used again for both lecture



and modules components during the ITP-16 course. While this space did have several advantages over Green 203, it was also met with significant facility issues that made implementing some aspects of the modules difficult.

One of the primary limitations of this space was the immobility of many of the work surfaces in the lab. As such, facilitating 20 students became a challenge because it was difficult to orient them in ways that was conducive to receiving instruction or working in groups larger than two. As can be seen in Figure 24, students could only be arranged in configurations that placed them either parallel or perpendicular to the presentation area, and in some cases, were only able to see the projection screen at extreme angles. This resulted in students sometimes getting out of their chairs to be able to view the presentation which resulted in obfuscating other students' view. Many students commented on this in their course evaluations when asked how the class could be improved with typical responses concluding with *"This course needs a larger space"* and *"I hope for a bigger lab in the future."*

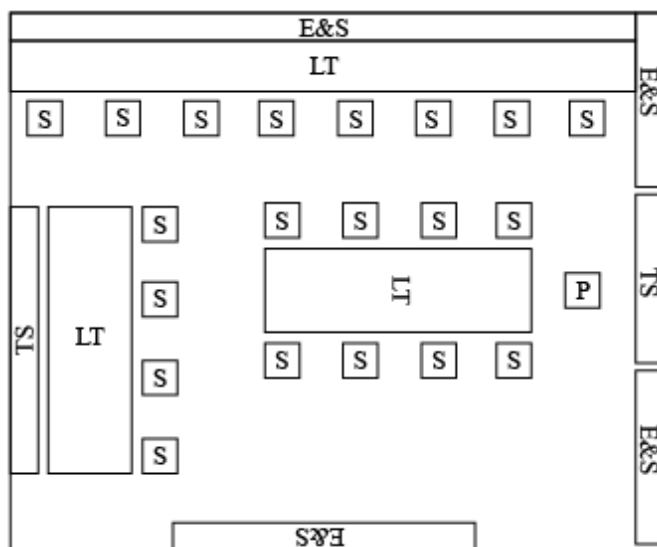


Figure 24 – Typical room layout of the Physical Computing Lab space at Berry College.

Working in groups larger than two was also hindered by the space. This issue was not as difficult as it was during the Georgia Tech courses because of the smaller class capacity, but it still limited larger group interactions that would bring diversity of thought to the brainstorming activities in the modules. Because the work surfaces were immovable, grouping students across from each other in most areas was impossible, meaning students could only meaningfully work with those directly adjacent to them. While in the case of Whitaker 1214 this allowed for groups of three students to work together, it was disadvantageous to do so in the Physical Computing Lab because most areas accommodate four students and would have resulted in some students left without a group.

One of the largest advantages to this space was that it used exclusively for this class during the semesters in which the course was taught. This made these offerings unique from all other previous treatments because it allowed for more flexibility in staging modules much further in advance than other spaces and allowed projects and equipment to be kept out because there was no concern about them interfering with other courses. Furthermore, while the immobility of the work surfaces created significant limitations, the larger dimensions of the tables were more conducive to working with large materials and students spreading out during the fabrication portions of the modules. For example, the work surfaces in this space were generally 96 inches long and 36 to 48 inches wide. For example, a typical sheet of foam board is 30x20 inches, thus the larger surfaces enabled students to more comfortably work with the material. This is in direct contrast to previous locations both at Berry College and Georgia Tech where work surfaces were less than 48 inches long and only 18 to 24 inches wide.

### 6.2.1.5 HackBerry Lab – Berry College

Beginning in the latter part of the spring 2016 semester, a purpose-built space was developed for maker-oriented courses to be taught in. This space, called HackBerry Lab, afforded a large amount of flexibility with respect to furniture, layout, and scheduling. As such, specific design decisions were made in configuring this space-based information gathered during previous implementations of the modules taught in other spaces. One consideration that was made was to develop a hybridized classroom and lab space that could accommodate a variety of activities such as traditional lecture-style classes as well as hands-on interactive labs.

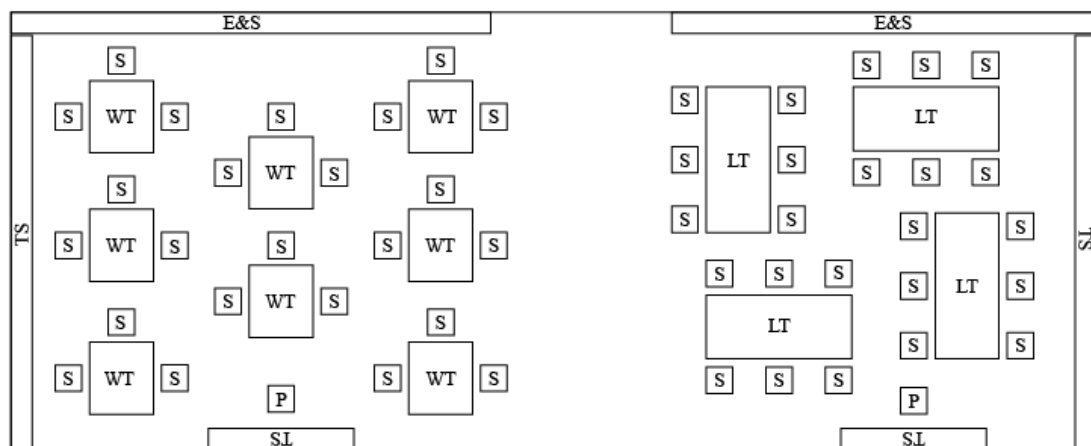


Figure 25 – Typical room layout of HackBerry Lab space at Berry College.

As seen in Figure 25 the space is divided into two areas with seating for 24 students in each. The area on the left, named the *design studio*, is designed around 48x48 inch tables with three students seated at each table. The area on the right, named the *clean prototyping lab*, utilizes 48x96 inch worktables that seat six students (three on each side).

The design studio is most often used for lecturing and some of the modules that are less resource intensive such as the Deconstruction of Technology and Circuit Design modules. The arrangement of the tables in this space allows for students to work in groups of three during collaborative activities, while also providing a focus on the front of the classroom for receiving instruction. The clean prototyping lab, however, is used for more resource intensive modules such as 3D Printing and Design, Wearable Technology Prototyping, and Interactive Prototyping with Arduino. These activities make heavy use of equipment which is located in the clean prototyping lab and affords larger work surfaces and a wider variety of group configurations. Depending on the particular module it is possible to reasonably group students into two groups of three or three groups of two. This gives the instructor a large amount of flexibility to adapt the modules and materials required based on overall class size. Having these two spaces used in conjunction with each other is additionally advantageous because it allows instruction and group collaboration to occur in one space and then the ability to transition to more rigorous hands-on exploration in the other space, all during the same class session. Furthermore, it is possible to stage materials and tools in the clean prototyping lab in advance of class without needing to worry about interference from other lecture-based classes taking place that day.

There are, however, still drawbacks to this space as presently implemented. Because the overall space has been divided into two areas, the overall capacity of classes is limited to 24 and the lack of walls between the two areas means that multiple classes cannot use the space simultaneously. Also, while maneuverability within the clean prototyping is relatively unrestricted, this is not the case with the design studio where

students often struggle to get past other groups. With this in mind, modules conducted in the design studio area generally are constrained to the traditional kit model, whereas modules conducted in the clean prototyping lab are able to utilize both traditional and workbench-style kits.

#### 6.2.1.6 Results

As a result of conducting these modules in a variety of classrooms, a number of design characteristics have become evident that should be considered when deciding if a space is conducive to conducting maker-oriented activities. These can be useful for both assessing existing spaces or designing new ones.

In terms of overall classroom size and square footage, the primary consideration that should be made is the active movement throughout the space required by the activities. Students often move around the space to access presentation areas and retrieve tools or materials. Instructors and teaching assistants also need to be able to easily access each student to monitor the work or offer help and feedback. As such, some types of classrooms are better suited than others. In this work, three common types of classroom spaces were considered: auditoriums, labs, and lecture spaces. Thirteen spaces were measured at both Georgia Tech and Berry College, including the spaces in which maker modules were conducted, in order to develop an area profile for each type of teaching space as seen in Table 34. Both the overall area of the classroom was measured, as well as the total area of the work surfaces in the space. The amount of free space per student was then calculated by subtracting the work surface area from the total classroom area to

develop an understanding of how students would be able to freely move around the room during modules.

*Table 34 –Free space among various classroom types at Georgia Tech and Berry College. Shaded rows indicate rooms in which modules were conducted.*

Campus	Building	Room	Classroom Type	Capacity (students)	Area (ft <sup>2</sup> )	Table Area (ft <sup>2</sup> )	Free Space per Student (ft <sup>2</sup> )
Georgia Tech	Whitaker	1214	Auditorium	68	2,400	204	32.3
Berry College	McAllister	100	Auditorium	40	864	150	17.9
Berry College	McAllister	115	Auditorium	62	870	209	10.7
Berry College	HackBerry	101	Lab	24	783	128	27.3
Berry College	McAllister	349	Lab	20	414	80	16.7
Berry College	McAllister	141	Lab	24	1,280	216	44.3
Berry College	McAllister	PhyCo	Lab	18	475	97	21.0
Georgia Tech	Clough	102	Lecture	80	3,200	400	35.0
Berry College	Green	203	Lecture	32	667	160	15.8
Berry College	HackBerry	100	Lecture	24	702	128	23.9
Berry College	McAllister	102	Lecture	36	714	150	15.7
Berry College	McAllister	235	Lecture	40	1,032	150	22.1
Berry College	McAllister	233	Lecture	24	1,120	120	41.7

Auditorium-style classrooms are generally characterized by their large seating capacities (around 60 students) with the focus of the room narrowing to a single presentation point in the room. The seating is often fixed, tiered, and relatively dense. Of the spaces studied, auditoriums afforded the least amount of free moving space with an average of 20.3 ft<sup>2</sup> per student. This amount of free space is also likely an overestimate since auditoriums generally allocate a large amount of space to the presentation area, which is largely unusable by students. Lab-style classrooms are generally designed around large tables where students work in groups. They facilitate working with instrumentation and students moving to access supplies and materials. When compared to the other two classrooms types, they accommodate the least number of students (around 20 students). Despite these smaller class sizes, they have the largest amount of free space with an average of 27.3 ft<sup>2</sup> per student. Finally, the characteristics of lecture-style

classrooms fall right between auditoriums and labs. Many of these classrooms are structured around having a small number of students (usually two to four) at a table and have an average class size 40 students. In terms of free space for student movement, they also fall in between auditorium spaces and labs with an average of  $25.7 \text{ ft}^2$  per student, which puts them relatively close to lab classrooms.

In terms of implementing the maker modules, Clough 102 provided the most flexibility for both students and instructors to move around the space. This was a result of both a generous amount of free space per student ( $35.0 \text{ ft}^2$ ), as well as the ability to configure the space. Whitaker also appeared to have adequate free space ( $32.3 \text{ ft}^2$ ), but the majority of that space was allocated to the auditorium presentation area which was mostly inaccessible to students. HackBerry Lab provided a moderate amount of space ( $27.3 \text{ ft}^2$ ), but it lacks any reasonable presentation space. All other spaces in which modules were taught (ranging from  $15.8 \text{ ft}^2$  to  $23.9 \text{ ft}^2$  per student) presented considerable mobility issues. On average, however, classrooms and lab spaces provide the most amount of free space for implementing modules in. The primary differentiation between the two comes down to overall course enrollment and capacity. For larger enrollments, lecture-style spaces provide a little less free space ( $25.7 \text{ ft}^2$  versus  $27.3 \text{ ft}^2$ ), but almost double the student capacity (40 students versus 20 students).

The ability to group students is also a key consideration when implementing maker-oriented strategies into a classroom. In addition to encouraging collaboration and divergent thinking, being able to put students into groups reduces the quantity of tools, materials, and time required to conduct a module. Thus, it seems reasonable to have students work with others and thus it is possible to set the lower bound of group sizes to

two students. With respect to the maker-oriented activities, it was observed that there can be an effective upper bound for group sizes as well. In some cases, students worked on the maker-oriented activities in the same groups they were arranged in for larger semester-long projects. This sometimes resulted in groups as large as five to seven students. This proved to be difficult to arrange any workspace large enough for all students to participate, as well as the modules themselves not having enough roles for each member to effectively contribute. With this in mind, large classes were usually arranged into groups of four, resulting in 20 groups for a large class of 80 students. This arrangement was reasonable with respect to the amount of time preparing and disseminating materials, while still allowing students to individually contribute to the module. Furthermore, it was possible to constrain student presentations to a reasonable amount of time to allow all groups to show their work. Thus, for the purposes of the maker modules, groups sizes between two and four students is encouraged. The actual group size chosen should be influenced by the possible seating arrangements, minimizing the workload on instructors and teaching assistants to prepare materials and supervise groups, and the ability for students to meaningfully contribute during the module activities.

Another characteristic of classrooms discovered was the exclusive use of the space for teaching the course. While it is not always feasible to dedicate an entire room to one class for an entire semester, spaces that afford flexibility in access and scheduling are desirable because of the large amount of time required to prepare the space for maker-oriented activities. In the case of the Physical Prototyping Lab, the exclusive use of the space afforded a number of advantages in terms of being able to stage the space well in



advance of the class, whereas heavily trafficked spaces like Clough often times dictated a very narrow window in which set up and clean up could occur. In these situations, set up and clean up often had to occur during class time which shortened the amount of time that could be spent on the modules.

Finally, the size and portability of work surfaces played a large role in how well classrooms were able to be adapted for maker-oriented activities. Tables that roll or are light enough to easily move allow the space to be arranged in such a way that supports both hands-on interactions in groups, as well as being able to receive clear directions from the instructor. With respect to the overall size of the table, there is some flexibility if tables can be combined to create larger surfaces. The ability to move tables to accommodate various class activities and configurations was mentioned frequently by students during post-course interviews.

*I thought it worked out very well because we could move the tables around and everyone had their own corner in the classroom, and we could change it to however we were comfortable with. (UID-F15)*

*I think that classroom is really nice, especially since the desks move really easily. So, we were able to move the desks into groups very easily to work, and then move it back for lectures and stuff like that. I think the way it was set up; it was very conducive to working together in groups and stuff. (MUC-S15)*

*All of a sudden, you just have a square or a block, or a big round table, or move everything out of the way and just have access to all the boards, and have enough room to put stuff up on the boards, and have enough room where all 10 teams could be spread out and not feel cramped. (MUC-S15)*

This approach was not without difficulties. During the first offering of the maker modules at Georgia Tech, there was initial confusion as to how tables would be arranged, resulting in a negative experience for students and time was wasted trying to identify a configuration that would meet the needs of both lecture-based instruction and hands-on activities. Two students noted during interviews:

*It was kind of loud and it wasn't very organized. The first day was kind of rough and the instructors didn't have the same idea in mind about how it would work. So that took a lot of time to figure out where to go. (UID-F15).*

*They moved all the tables to the center and then rotated it around - it was fine, but it was a time crunch. (UID-F15).*

Furthermore, it became apparent that in larger classrooms with more students, trying to determine a single table configuration that met the needs of lectures and modules was impractical and tables were only rearranged for sessions in which modules occurred upon future implementations. This early struggle was reflected in students'

frustration in participating in lectures during the first classroom treatment at Georgia Tech. For example:

*The space did not work well. It was really overwhelming to have so many people in the same classroom. The way that the tables and the chairs are set up were not ideal. If you're too far back, you can't listen and that happened to me in several presentations so I couldn't contribute. I would say for that, it was ineffective. (UID-F15).*

While implementing the maker modules throughout the various classrooms, the Clough and HackBerry Lab tables were the least restrictive, whereas the tables in Green and Whitaker were the most restrictive. This restrictiveness manifest itself in two significant ways. The first was in the selection of materials that could be used in the maker modules themselves. Before each treatment, the instructors visited each space to determine how each module would be conducted. As part of that visit, tables were measured so that appropriate materials could be selected. For example, in the Rapid Foam Board Prototyping module, students are typically provided with several sheets of 20x30” foam board to work with. This would have proven to be difficult for students in both the Whitaker classroom as the tables are only 18” deep, because they would be unable to cut the length of the material without going off the edge of the table. To accommodate this foam board sheets were halved to make 20x15” sheets, though this limited the overall scale of prototypes students could make during the exercise. The other way in which the restrictiveness of table size influenced modules was observing how

students interacted with each other during group design activities. When students were restricted to narrow tables, they generally arranged themselves along the length of the table which reduced the amount of face to face interaction during the activity and in some cases resulted in students at the far ends of the table and never engaging each other at all. With larger tables, however, students generally arranged themselves around the perimeter of the surface, resulting in more interaction and engagement with each group member.

In order to help quantify these observations, a survey was conducted to measure the table areas of a variety of classrooms. The amount of table space allotted for each student was calculated in Table 35. When analyzed, it was revealed that auditoriums provide the least space to students with an average of 3.4 ft<sup>2</sup>, while labs provide the most with an average of 5.9 ft<sup>2</sup>. Again, lecture spaces fall between the two with the average space allotting 4.7 ft<sup>2</sup> for students.

*Table 35 – Table space among various classroom types at Georgia Tech and Berry College. Shaded rows indicate rooms in which modules were conducted.*

Campus	Building	Room	Classroom Type	Capacity (students)	Movable Table	Table Area (ft <sup>2</sup> )	Table Space per Student (ft <sup>2</sup> )
Georgia Tech	Whitaker	1214	Auditorium	68	No	204	3.0
Berry College	McAllister	100	Auditorium	40	No	150	3.8
Berry College	McAllister	115	Auditorium	62	No	209	3.4
Berry College	HackBerry	101	Lab	24	No	128	5.3
Berry College	McAllister	349	Lab	20	Yes	80	4.0
Berry College	McAllister	141	Lab	24	No	216	9.0
Berry College	McAllister	PhyCo	Lab	18	No	97	5.4
Georgia Tech	Clough	102	Lecture	80	Yes	400	5.0
Berry College	Green	203	Lecture	32	No	160	5.0
Berry College	HackBerry	100	Lecture	24	Yes	128	5.3
Berry College	McAllister	102	Lecture	36	Yes	150	4.2
Berry College	McAllister	235	Lecture	40	Yes	150	3.8
Berry College	McAllister	233	Lecture	24	Yes	120	5.0

There is an underlying consideration that must be made when considering these values. With this data, it would seem that there would be no difference between the

student work experience in Clough 102 and Green 203 as both have 5.0 ft<sup>2</sup> of table space per student, with each table measuring 2x5 ft. However, as previously mentioned students succeeded quite well in Clough 102, whereas Green 203 had to be abandoned for the maker modules. The primary difference came down to configurability. Because the tables were able to be reconfigured in Clough, the instructors were able to combine two tables to create a 4x5 ft. table that better supported group interactions. Furthermore, it is possible to have certain table geometries that do not accommodate the hands on learning. Long and narrow tables may provide an overall similar square foot per student amount (e.g. 1x5 ft.), but if not configurable, will not provide an adequate amount of space to work. From this experience, we can conclude that movable tables that have a minimum of 2 feet in depth and at least 5 ft<sup>2</sup> of table space per student is ideal.

Students also took notice of the difference between classes that were conducted in lecture rooms such as Clough 102 versus auditorium-style spaces like Whitaker 1214. Students responded that auditorium spaces focused all the attention on a single presenter, rather than among others in the class and dissuaded participation and discussion. During MUC-S15 and MUC-S16 conducted students made the following observations lecture versus auditorium-style spaces:

*The seating is probably the most immediate difference in terms of everyone on an equal level, which I thought was interesting, because there are not a whole lot of classes devoted to lectures. So, the benefit of the space is not a whole lot, but I think that everyone being on the same level leads to a little bit more intimate environment for discussion. I think when you sit above someone or below*

*someone, that kind of creates this weird imbalance in the room for discussion.*

*The movable tables were nice, because it allowed it us to completely change the room into something that would be useful for creating a project. (MUC-S15).*

*I like that we were all in tables instead of [auditorium] style, just because it made it all like peer-like instead of presenter and other people. I feel like in [auditorium] style, you can kind of blend in really well. Whereas, with the tables, you're more community-like. (MUC-S16).*

As existing spaces are considered or new spaces are developed to support maker-oriented learning, it is important to consider the overall classroom size with respect to both the overall area, table selection, and classroom capacity, in order to maintain feasible workspaces and allowing enough room for students to freely move around the space.

### *6.2.2 Artful Surfaces*

Supporting open-ended project-based work in maker-oriented learning requires a unique combination of both low-tech and high-tech devices. While 3D printers and laser cutters certainly play an important role in implementing maker modules in classrooms, whiteboards, projectors, and sticky notes also contribute to the classroom environment. These various forms of storing and displaying thoughtful information are called *artful surfaces*. This term came as a result of researchers studying design studios and understanding how creative thought was informing the space. Vyas defines artful surfaces

as “surfaces that designers create by externalizing their work-related activities, to be able to effectively support their everyday way of working” [72].

In this work, we will extend the concept of “work-related activities” to include work performed by instructors and students in classrooms. This approach is well-supported as chalkboards, a form of artful surface, have been a staple of classrooms for hundreds of years. However, the nature of these artful surfaces in classrooms has been evolving as more active learning practices have made their way into curriculum. Brooks noted in a survey of classroom-based design practices that "courses now emphasize hands-on experimentation, technological visualizations and demonstrations and other collaborative active learning techniques; the classrooms were configured with round student tables, laptop connections, display screens and marker boards around the circumference of the room" [73]. These technologies, he argues, yield benefits for “improved cooperative learning, enhance in-class problem solving, and increase faculty–student interaction” when compared to traditional classroom spaces [73].

Vyas also lays out four specific purposes of artful surfaces that align well with the learning goals associated with maker-oriented learning and the maker module framework as described in Chapter 4. According to Vyas, they are “establishing a common understanding of a complex design idea or a task; organizing and planning design activities; describing design in a rich, narrative and metaphorical way; preserving the memory of a design project and the ‘reasoning’ behind it” [72]. Using artful surfaces to help establish a common understanding informs the *expectation and exposition* steps of the maker module framework that help establish a foundation of motivation and underlying principles and terms that will shape and define the work. Organizing and

planning design activities, on the other hand, is supported by the central element of the *exploration* step in the maker modules where students are able to develop creative hands-on artifacts that reflect the curricular concepts. Describing the design is also paralleled in the *explanation* step as students are able to use both the physical artifacts created as well as the information stored in artful surfaces to present and defend their work during critique. The last purpose Vyas proposes for these surfaces are to preserve the work as well as the motivation for it, which is often encapsulated in both the *explanation* and *expansion* steps where students are able to extend the principles learned during in-class activities to other contexts outside of the classroom.

In addition to these goals as described by Vyas, Kuhn adds some additional goals when describing resources in design-focused physical prototyping. Kuhn describes that such resources should allow participants to “deal with open-ended problems; carry out rapid design iterations; use heterogeneous media; support formal and informal critiques; and make creative use of constraints” [74]. In this study, Kuhn was expressly looking at how elements of traditional architectural design studios could be implemented into software development classrooms, and thus is reasonable to consider similar implementations into HCI-focused spaces. These goals demonstrate a close alignment with how maker-oriented curriculum is structured and suggest that thoughtfully designed spaces can influence the quality of work that can occur in such places.

#### 6.2.2.1 Characteristics of Artful Surfaces

Throughout the process of delivering maker modules in classrooms, a number of artful surfaces were utilized in order to help support the activities. This included support



for instructors presenting content, students developing the work, as well as in-class critiques. Over several iterations, a number of characteristics emerged that helped develop an understanding of the role of each surface in maker-oriented curriculum. Vyas defined four distinct types of artful surfaces that provide a starting point for understanding how these surfaces can affect the implementation of the maker modules. These types are personal, shared, project, and live artful surfaces [75].

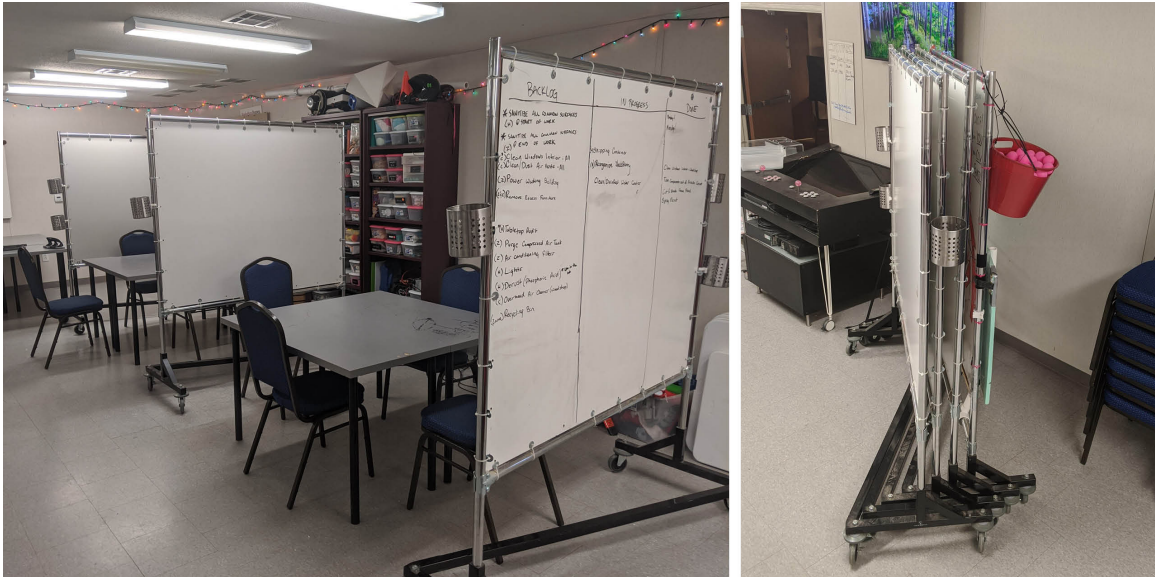
Personal artful surfaces are created by individuals and are generally used within spaces that are exclusively occupied by the creator [75]. This type of surface is the least common within the scope of implementing maker modules in classrooms because many of these spaces preclude students from having personalized work areas. There can be exceptions to this as some studio spaces can provide dedicated work areas for students. Shared surfaces, on the other hand, are more prevalent as they are generally located in areas that are accessible by larger groups and used to share information among participants in the space [75]. Project-specific spaces focus on tracking the coordination and progression of work being accomplished on specific assignments [75]. Like personal surfaces, these can be difficult to allot space for in classrooms that are multi-purpose, but can, on occasion, be implemented. The final surface type, live surfaces, are the most prominent among classroom-based instruction. These surfaces are temporary and meant to help capture divergent brainstorming activities and help improve communication and collaboration among students [75]. Given that many practical implementations of maker-oriented curriculum occur in spaces that are not exclusive to this type of instruction, live surfaces are commonly used because they do not require long-term utilization of any surfaces that may disrupt other courses that may also be using the space.

In addition to Vyas’ categorization of artful surfaces, several other characteristics were explored with respect to their impact and utility in delivering the maker modules. These characteristics include mobile, multimodal, presentable, durable, reusable, and templated, as summarized in Table 36.

*Table 36 – Summary of additional artful surface characteristics considered when designing maker-oriented classrooms.*

Characteristic	Summary Description
Mobile	Possesses the ability to be moved around the classroom space
Multimodal	The ability for the surface to support a variety of interactions or media
Presentable	Can be shown or demonstrated to the entire class for feedback or critique
Durable	The duration in which information is intended to stay on the surface
Reusable	Can the surface be reused once it has been utilized
Templated	Does the surface constrain the way in which information is recorded

*Mobile* artful surfaces refer to any surface that can be easily relocated around a classroom space. Mobility is advantageous for artful surfaces because it can allow the space to be quickly reconfigured for maker-oriented instruction and create impromptu presentation spaces or work areas. One of the most common types of mobile artful surfaces are rolling whiteboards or mobile Z-rack whiteboards [76]. Z-rack whiteboards, a concept developed at the Stanford d.school, are created by repurposing a common dry cleaner’s garment rack and affixing whiteboard material to it to create large surfaces that students can use throughout a classroom space [77]. Furthermore, the z-shaped base of the design allows multiple boards to be stacked together to minimize the amount of space required to store the boards while not being used (Figure 26). When deployed in a classroom, the boards can also function as both visual and sound barriers between groups working on design-based tasks. This is particularly important in classrooms where it is not possible to sufficiently spread out student groups because of limited square footage.



*Figure 26 – Z-rack whiteboards used to create walls and writing surfaces impromptu design spaces (left). After use, they can be stacked to for storage to reduce their overall footprint (right).*

Another example of mobile artful surfaces is remountable whiteboards. These boards can be easily mounted and unmounted from wall pegs that allow students to work on them at their group tables, but easily replace them in order to present their work to the entire class (Figure 27). They are similar to the Z-rack whiteboards, as well, inasmuch that they are stackable, which reduced the need to dedicate much space to their storage. It is possible to distribute them among groups during a design exercise, and then have each group return them to a single centralized point in the room to present their work, thus maximizing their utility in the classroom, while minimizing the amount of space required to store them.



*Figure 27 –Remountable whiteboards can be distributed to groups or individual students for rapid design exercises (left). The whiteboards can then be remounted to the wall for presentations or critique (center). Multiple whiteboards stack on the mounts for compact storage (right).*

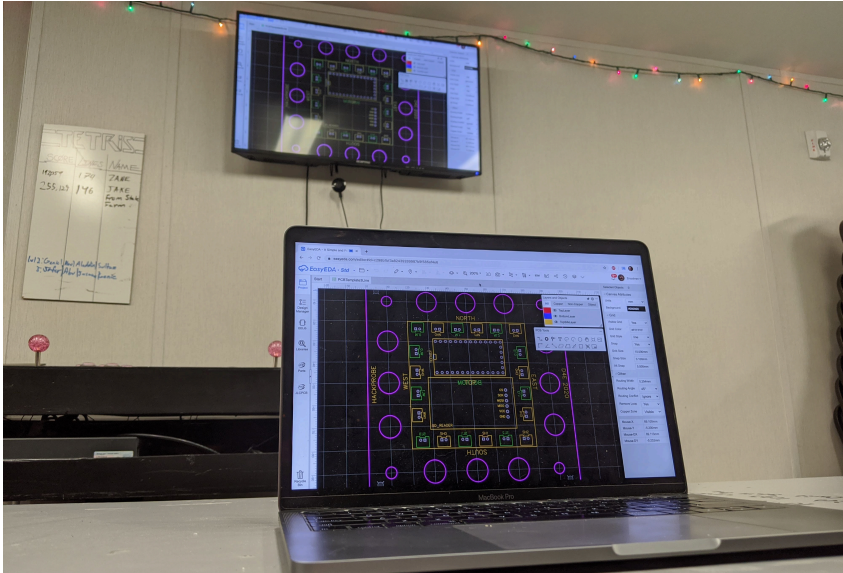
*Multimodal* surfaces are able to display a variety of mediums allowing students a large amount of flexibility in displaying content that either serves to inspire new ideas or organize existing ideas. Traditionally these surfaces have been fabricated from materials that allow users to attach items to the board using pushpins and are a common item in art and design studios. The flexible nature of such surfaces allows them to be easily adapted to maker-oriented instruction as they are able to display traditional design artifacts such as sketches, swatches, and printed images. During instructional activities during later implementations of the maker modules, students also used the physical multimodal surfaces to showcase non-traditional artifacts such as foam board mock-ups and printed circuit boards (Figure 28).



*Figure 28 –Pin up boards or cork boards are a common non-digital multimodal surface. A variety of visual mediums can be affixed to them such as printed visuals (left) or physical samples or swatches – in this case printed circuit boards (right).*

Multimodal surfaces are not necessarily constrained to physical boards. The increasing availability of digital display technologies also provide the opportunity for students to share a variety of artifacts through both wired and wireless connections to these displays. In practice, it was observed that students used digital displays such as projectors and monitors to show both work in progress and finalized prototypes. One approach taken in the modules taught in HackBerry Lab made use of networked televisions using Chromecast – a technology that allows students to mirror their computer or mobile phone screens wirelessly on a wall-mounted television screen. This approach allowed students to show a wide range of digital artifacts created during the maker modules including 3D models, Arduino code, and circuit designs (Figure 29).





*Figure 29 – Wireless networked displays allow students to mirror their computer displays to show digital work created during maker modules.*

During the exposition, exploration, and explanation portions of the maker module framework, it is important for instructors to present information and for students to be able to showcase their work. As such, surfaces that are *presentable* are a key characteristic for many classroom-based artful surfaces. Presentable surfaces are those that provide easy visibility to either the entire class or subsections of the class for the purpose of evaluation, critique or soliciting feedback. Such surfaces are also instrumental in demonstrating physical techniques that would otherwise be difficult for classroom participants to observe. They can be either digital or non-digital surfaces, as long as they are able to provide adequate resolution (or in some cases magnification) of the work. For example, during rapid foam board prototyping exercises, instructors demonstrate four sample joints that can be made using X-Acto knives, hot glue guns, and foam board. The scale of these joints is so small that it could not be reasonably demonstrated to anyone

more than a few feet away. In such scenarios, artful surfaces such as projection screens coupled with a document camera, become invaluable when conducting these modules. Furthermore, the wall-to-wall whiteboard surfaces found in both the Clough and Whitaker classrooms allowed the instructors to create multiple presentation surfaces to conduct critique sessions with various student groups arranged throughout the space. This arrangement resulted in various “round-robin”-style critique sessions where students could travel between presentations and give feedback on multiple projects during one class session because of the prevalence of many presentable artful surfaces.

The *durability* of artful surfaces should also be carefully considered. In this context, durability refers to the duration in which information is intended to remain on the surface. During many of the maker module implementations, less durable surfaces were used because the information being gathered was only required for a few minutes or maybe hours. As discussed in section 2.2.1, one of the primary constraints of implementing maker-oriented curriculum is the non-exclusive use of classroom facilities. As such, more durable surfaces such as scrum boards, which are intended to maintain information for weeks or months, can be more difficult to implement because they require uninterrupted use of the resource while other classes are accessing the space (Figure 30). This can be curtailed through using digital resources that do not consume physical resources inside the classroom, though the lack of a persistent physical presence can sometimes result in students not frequently referencing such resources. Nevertheless, since many of the maker modules focus on rapid prototyping activities, there is a relatively low requirement for durable artful surfaces, and as such, surfaces that are intended for storing information for only a small amount of time should be sought out.

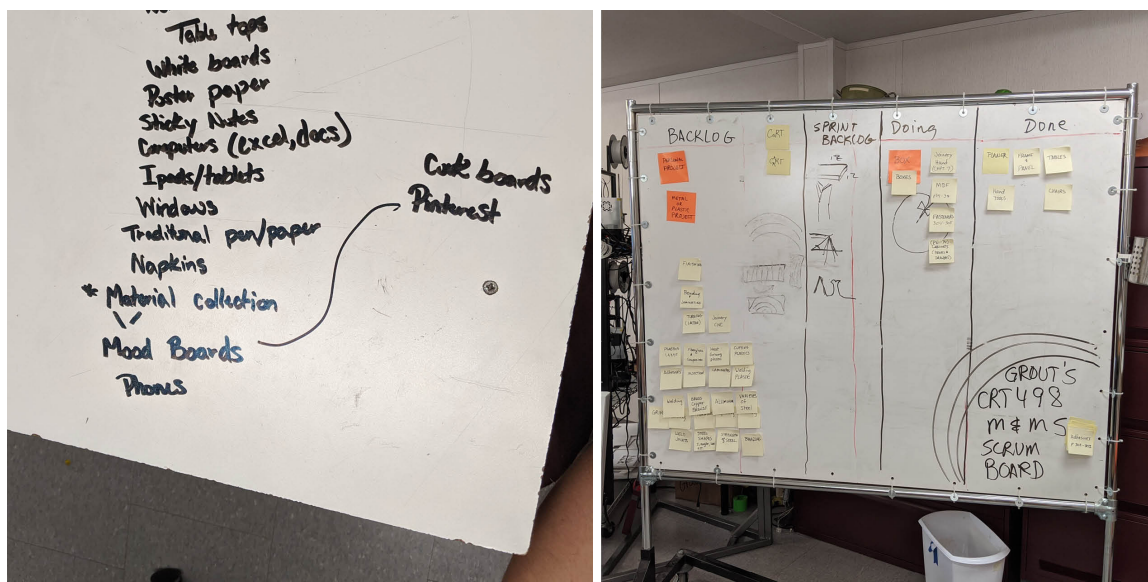
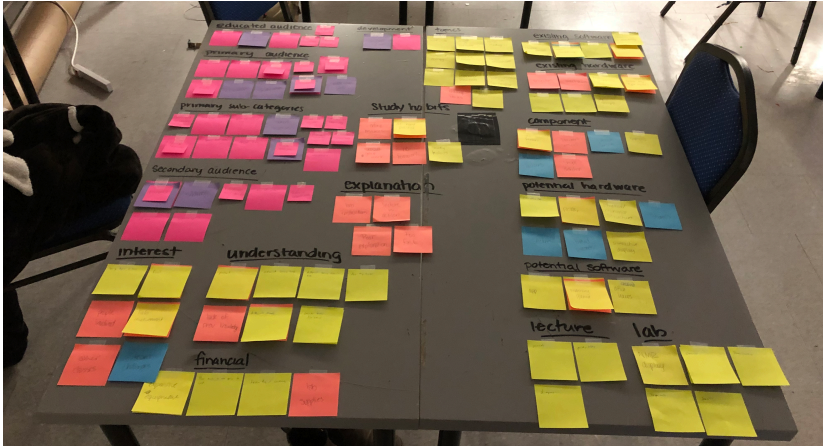


Figure 30 – Artful surfaces such as whiteboard tables (left) are less durable than scrum boards (right) because the amount of time the information is intended to be stored is significantly shorter (minutes versus months).

The *reusability* of artful surfaces is also a distinguishing factor in determining how students are able to develop and document their work during the maker modules. In most cases, surfaces that were highly reusable, such as whiteboards, were often utilized because they reduced the overall physical requirements for the classroom. However, non-reusable surfaces can be helpful in some limited cases. During the *exploration* element of some modules, students are encouraged to engage in divergent brainstorming, resulting in a wide variety of ideas. They then combine their ideas with others in the class and organize their thoughts to find common themes. Organizing these thoughts can be difficult when done with whiteboards or tables and are instead encouraged to use sticky notes. While these notes are one-time use only, the ability to reorganize the notes contributed to more fluid interactions among students.





*Figure 31 – Non-reusable artful surfaces such as sticky notes can provide an advantage over reusable surfaces because of the ability to easily reorganize and group them.*

The last characteristic of artful surfaces that played a role in the execution of the maker modules were surfaces that were *templated*. This characteristic denotes surfaces that constrain the type of information or the way in which information is stored on the surface. By constraining certain types of surfaces, students are able to organize information in a way that is easily accessible and understandable. One common example that was developed in classrooms that had access to prototyping technologies was using the surfaces of the equipment as an artful surface to track information about the work being performed. Keeping track of what students were creating on the 3D printers, for example, became important because students would start a print and then leave and return later. Knowing what was printing, who was printing it, and how long it would be printing for helped coordinate other students that were competing for the same resource (Figure 32).

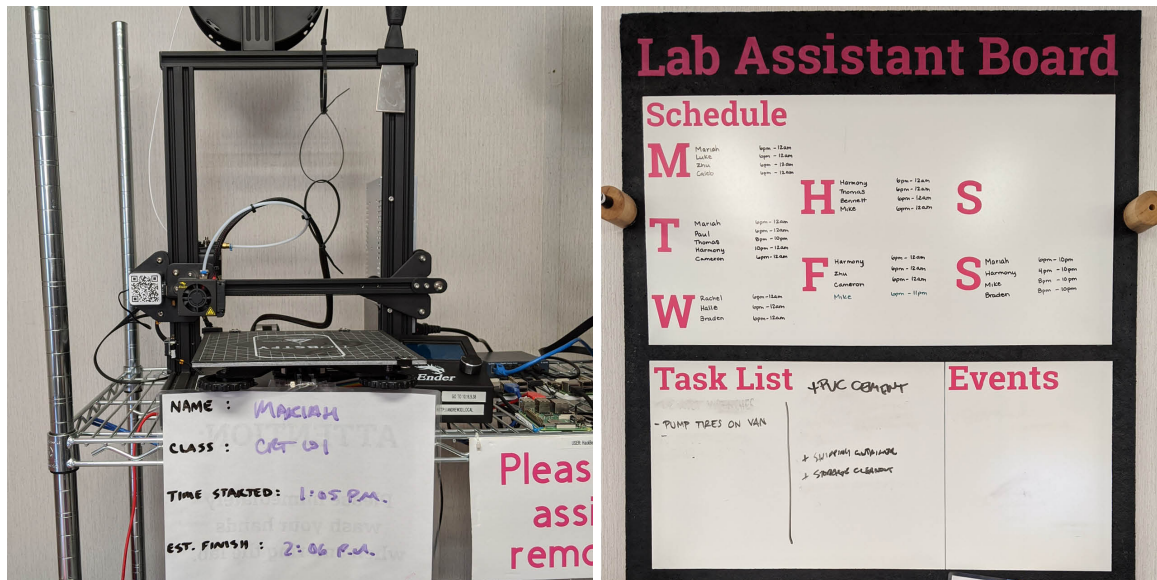


Figure 32 – In order to better organize and focus information, templated artful surfaces constrain how users are able to interact with them as seen on this 3D printer (left) and scheduling board (right).

#### 6.2.2.2 Results

Artful surfaces can have a significant impact on how maker modules are implemented in classrooms. Common presentation equipment such as projectors and whiteboards are a bare minimum, but the inclusion of additional surfaces can aide with each step of the maker module framework. One of the largest factors to consider when determining which artful surfaces to include in a maker-oriented classroom is the exclusivity of use of the room. Rooms that are used only for maker-oriented classes generally provide more flexibility. Where exclusivity is not possible, designers of maker-oriented classes should especially consider surfaces that are mobile, multimodal, presentable, and reusable.

A survey of the classrooms in which maker-oriented curriculum were conducted resulted in the identification of 15 different artful surfaces (Table 37). Of the five spaces

studied, the classrooms in the Whitaker (Georgia Tech) and Green (Berry College) buildings had the least number of artful surfaces. This may be a result from these classes being designed for traditional lecture-style instruction. The experimental classroom in Clough provided slightly more surfaces with the addition of metallic-backed whiteboards that afforded multimodal interaction as students were able to not only draw on these boards, but hang various materials from the boards using magnets. The prevalence and utility of the whiteboards within Clough 102 were specifically mentioned during post-course interviews with students. Students noted the following:

*It was nice to have the whiteboards all around the classroom. So, if we needed to sketch something out, we could just go up there and draw it. Everyone had their own whiteboard space, so that was good. (MUC-S15).*

*It worked really well. We have the same similar setup where it's whiteboard walls all around. You can go around to look at somebody's dropdown notes, put a sticky note up on somebody else's stuff. So that helped a lot. (MUC-S16).*

The Physical Computing Lab in the McAllister building at Berry College had eight artful surfaces, which was the result of having exclusive use over the space for the maker-oriented class being taught there. Finally, HackBerry Lab at Berry College had a total of 12 artful surfaces, which allowed a diverse set of student and instructor interactions in each of the maker modules. This diversity is the result of the space having been specifically designed to support maker-oriented learning.

*Table 37 – Comparison of available artful surfaces in maker-oriented classroom spaces.*

Surface	Clough	Whitaker	Green	McAllister	HackBerry
Wall Mounted Whiteboard	X	X	X	X	
Metallic Whiteboard	X				
Z-Rack Whiteboard				X	X
Scrum Board					X
Pinup Board					X
Remountable Whiteboard					X
Dry Erase Desk/Table				X	X
Lab Equipment				X	X
Networked Display					X
Personal Paper Products	X	X	X	X	X
Wall/Window				X	
Laptop/Tablet	X	X	X	X	X
Projector	X	X	X	X	X
Easel Pad			X		
Document Projector	X	X			X

With regard to the individual artful surfaces found in the classrooms, each was categorized using the criteria discussed in 6.2.2.1 (Table 38). From this study, a few interesting comparisons can be made among several similar surfaces. Such comparisons can be useful when deciding which types of surfaces to incorporate into a classroom that will be hosting maker-oriented curriculum. As mentioned previously, whiteboards are a common staple in most classrooms, but in this study five types of whiteboards were found to be in use: wall mounted whiteboards, metallic whiteboards, Z-rack whiteboards, remountable whiteboards, and dry erase desks and tables. While these surfaces share a variety of characteristics such as durability and reusability, it can be seen that Z-rack whiteboards and remountable whiteboards have mobility whereas the others do not. Mobility, as discussed, can provide significant advantages in conducting modules and may be favored over other types of whiteboards when designing a classroom space.

*Table 38 – Survey of characteristics found among common artful surfaces found in maker-oriented classrooms.*

<b>Surface</b>	<b>Mobile</b>	<b>Multimodal</b>	<b>Presentable</b>	<b>Durable</b>	<b>Reusable</b>	<b>Templated</b>
Wall Mounted Whiteboard	No	No	Yes	Hours	Yes	No
Metallic Whiteboard	No	Yes	Yes	Hours	Yes	No
Z-Rack Whiteboard	Yes	No	Yes	Hours	Yes	No
Scrum Board	No	No	Yes	Days	Yes	Yes
Pinup Board	No	Yes	Yes	Hours	Yes	No
Remountable Whiteboard	Yes	No	Yes	Hours	Yes	No
Dry Erase Desk/Table	No	No	No	Minutes	Yes	No
Lab Equipment	No	No	No	Minutes	Yes	Yes
Networked Display	No	Yes	Yes	Minutes	Yes	No
Personal Paper Products	Yes	No	No	Minutes	No	No
Wall/Window	No	No	Yes	Hours	Yes	No
Laptop/Tablet	Yes	Yes	No	Minutes	Yes	No
Projector	No	Yes	Yes	Minutes	Yes	No
Easel Pad	Yes	No	Yes	Hours	No	No
Document Projector	No	No	Yes	Minutes	Yes	No

This comparison of artful surfaces may also help to find alternatives to technologies that may not be available to the instructors teaching in these classrooms. For example, in classrooms where projectors are not available, the information presented in Table 39 shows that networked displays may be a reasonable alternative because there are no characteristic differences between them. Similarly, where remountable whiteboards are not an option, easel pads could be used instead with the only difference among them being reusability.

Table 39 – Difference matrix showing relationship of artful surfaces to each other (lower values represent more similar surface).

	Standard Whiteboards	Metallic Whiteboards	Z-Rack Whiteboards	Scrum Board	Pinup Board	Remountable Whiteboards	Dry Erase Desks/Tables	Lab Equipment	Networked Displays	Paper Products	Walls/Windows	Laptops/Tablets/Phones	Projectors	Easel Pads	Document Projectors
Standard Whiteboards	-	1	1	1	1	1	2	3	2	4	0	4	2	2	1
Metallic Whiteboards	1	-	2	2	0	2	3	4	1	5	1	3	1	3	2
Z-Rack Whiteboards	1	2	-	2	2	0	3	4	3	3	1	3	3	1	2
Scrum Board	1	2	2	-	2	2	3	2	3	5	1	5	3	3	2
Pinup Board	1	0	2	2	-	2	3	4	1	5	1	3	1	3	2
Remountable Whiteboards	1	2	0	2	2	-	3	4	3	3	1	3	3	1	2
Dry Erase Desks/Tables	2	3	3	3	3	3	-	1	2	2	2	2	2	4	1
Lab Equipment	3	4	4	2	4	4	1	-	3	3	3	3	3	5	2
Networked Displays	2	1	3	3	1	3	2	3	-	4	2	2	0	4	1
Paper Products	4	5	3	5	5	3	2	3	4	-	4	2	4	2	3
Walls/Windows	0	1	1	1	1	1	2	3	2	4	-	4	2	2	1
Laptops/Tablets/Phones	4	3	3	5	3	3	2	3	2	2	4	-	2	4	3
Projectors	2	1	3	3	1	3	2	3	0	4	2	2	-	4	1
Easel Pads	2	3	1	3	3	1	4	5	4	2	2	4	4	-	3
Document Projectors	1	2	2	2	2	2	1	2	1	3	1	3	1	3	-

### 6.2.3 Power, Equipment, and Storage

Many of the maker modules require access to materials, tools, equipment, and electricity to power the technology used during class sessions. These unique demands necessitate consideration of power demands, placement of equipment, and storage solutions that may not have been previously incorporated into a classroom space. Throughout the early implementations of the maker modules, several important observations were made regarding the physical demands such activities can have on a space's infrastructure.

#### 6.2.3.1 Power

Every maker module detailed in this work uses equipment that requires electrical power. In some cases, the amount of power is quite small where only a projector and laptops are required. In other cases, however, the amount is quite significant and can overwhelm the traditional power infrastructure of a classroom if not managed appropriately. Furthermore, providing access to electrical outlets can be problematic in some classrooms where those outlets are infrequent or inconveniently located. Providing ample power in convenient locations is not only important to the smooth execution of maker modules, but also a significant component of classroom safety.

Classrooms are generally outfitted with various electrical outlets in order to provide power to equipment and devices. In traditional classrooms, the availability of this electricity may be constrained to only powering a few essential items such as a projector and computer for the instructor. On the other hand, in lab environments the amount of power available may be substantial and necessary for running industrial-sized pieces of equipment or tooling. As such, it is important to consider that amount of power available in a given space and tailor the maker modules around what is both practical and safe. One approach to structuring the tools and equipment used in the maker modules around the electrical capabilities of a classroom is through using a power budget worksheet (Table 40). This worksheet collects and calculates a number of factors that can be helpful when deciding the following items:

1. *What are the electrical capabilities of a particular classroom?*
2. *What are the electrical requirements for individual tools or pieces of equipment?*

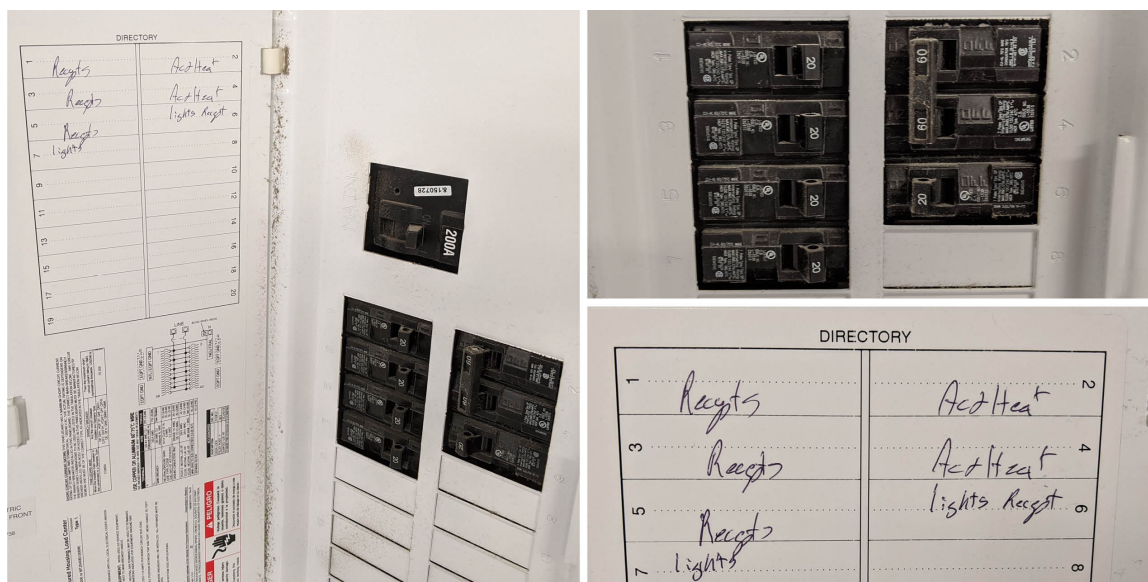
3. *How many tools per group are reasonable in order to stay within the electrical constraints of the space?*
4. *Is a certain class size appropriate for conducting maker-oriented activities in a given classroom with respect to its electrical capacity?*

*Table 40 – A sample power budget worksheet for the 2D Design and Fabrication maker module. This shows a positive load capacity remaining that indicates that the classroom's electrical infrastructure meets the demands of the activity.*

<b>Maker Module</b>	<b>2D Design and Fabrication</b>							<b>Classroom Information</b>	
<b>Equipment</b>	<b>Voltage</b>	<b>Power</b>	<b>Current</b>	<b>Total Items</b>	<b>Amps</b>	<b>Total Items</b>	<b>Total Amps</b>	<b>Class Size (Total Students)</b>	
	Volts	Watts	Amps	per Group	per Group	per Class	per Class	Students Per Group	
Hot Glue Guns	120	100	0.83	1	0.83	8	6.67	Total Groups	8
Projector	120	432	3.60	0.125	0.45	1	3.60	Circuit Rating (Amps)	20
Laptops	120	65	0.54	3	1.63	24	13.00	Total Circuits	4
Vinyl Cutter	120	120	1.00	0.125	0.13	1	1.00	Total Circuit Capacity (Amps)	80
Laser Cutter	120	760	6.33	0.125	0.79	1	6.33		
						<b>Total Amps</b>	30.60	<b>Load Remaining</b>	49.40

The first question addresses discovering the electrical capabilities of a specific classroom. This can be determined in two ways. The first is through consultation with the building's maintenance crew or electrician, who may be able to offer specific advice concerning the overall capabilities of a space. The second can be ascertained individually if the room provides access to a well-documented fuse box (Figure 33).

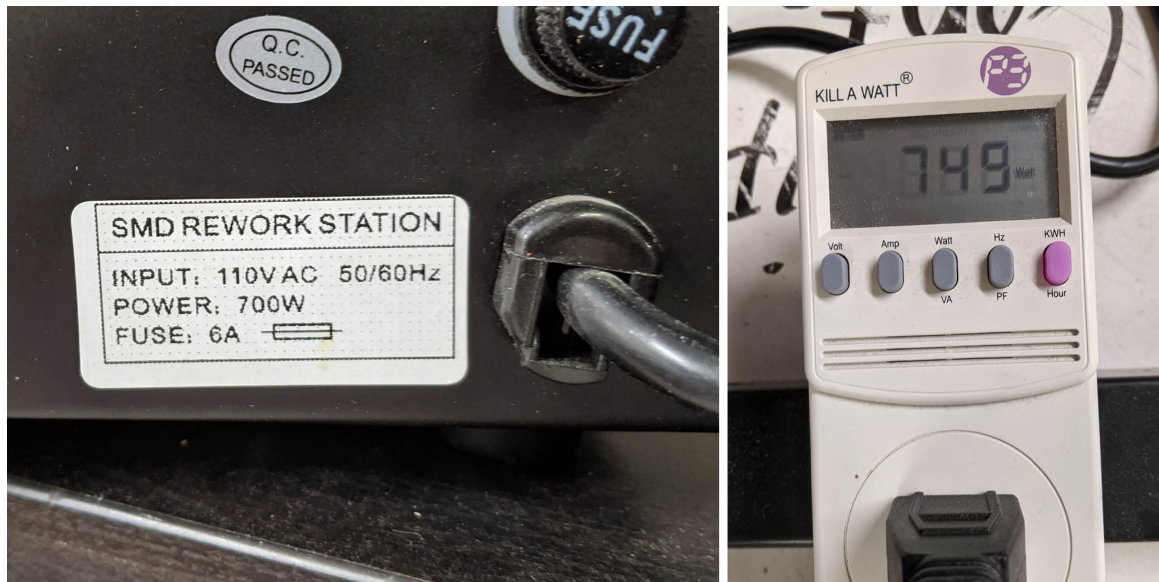




*Figure 33 – A well-documented fuse box provides insight into the individual amperage capacity of a given circuit, as well as the number of circuits available to a classroom space. In this case, three circuits are dedicated to outlets with 20 amps allotted to each circuit.*

The total circuit capacity for the classroom can then be obtained by multiplying the individual circuit rating by the total number of circuits. It should be noted, however, that electrical loads should be spread evenly across these circuits, as overloading any single circuit will, at best, result in tripping a fuse, and at worst, causing an electrical fire.

The second question helps instructors ascertain the individual power requirements of each tool used in the maker modules. These power requirements can generally be found on the device itself, usually on a label or stamped into the equipment near the power cable or on/off switch. In most cases, this label will indicate the operating voltage of the device as well as its power consumption in watts. In case this information is not available, the power requirements of the device can be gathered empirically through the use of an electricity usage monitor, such as a Kill A Watt (Figure 34).



*Figure 34 – The power rating for a soldering station located on a decal near the power cable indicates it consumes 700 watts (left). An empirical measurement of its power consumption using a Kill A Watt indicates that its usage is closer to 750 watts (right).*

Empirically measuring the power consumption of a device was helpful in discovering that some devices consumed more power than they were labelled. In the case of a single device, this difference may be negligible, but when using several devices can represent a significant draw on electrical resources. For example, a soldering iron station rated at 700 watts was found to actually draw 750 watts. In one of the implementations of the maker modules, 12 of these stations were used, resulting in an additional 600 watts of power being consumed which is almost the equivalent of another soldering station. It should be noted that devices can consume different amounts of power when performing different functions and should be measured accordingly. The 3D printers used in the maker modules used 270 watts during their heating cycle, but only 65 watts during printing operations. In total, 15 different tools were surveyed that were used during the maker

modules and the results have been compiled in Table 41. Power ratings may vary by brand of tool, so these figures should be considered as general guidelines and not exact.

*Table 41 – Survey of power requirements for tools used in eight maker modules.*

<b>Tool</b>	<b>Voltage (Volts)</b>	<b>Power (Watts)</b>	<b>Current (Amps)</b>
Hot Glue Gun	120	100	0.83
Laptop (plugged in)	120	65	0.54
Laser Cutter	120	760	6.33
Vinyl Cutter	120	120	1.00
Heat Press	120	1500	12.50
3D Printer	120	270	2.25
Electric Kettle	120	1500	12.50
Hot Wire Cutter	120	1500	12.50
Drill Press	120	180	1.50
Miter Saw	120	1000	8.33
Air Compressor	120	175	1.46
Band Saw	120	320	2.67
MIG Welder	240	43000	179.17
Soldering Station	120	750	6.25
Projector	120	432	3.30
Fume Extractor	120	50	0.42

The third and fourth question answered by the power budget worksheet are interrelated and rely on data gathered from the first two questions. Once the capabilities of a classroom are determined and the tools required for the maker module have been rated, an instructor can then manipulate the overall class capacity, group size, and number of tools given to each group in order to stay within an acceptable power range. This balancing becomes particularly important with modules that use a significant number of tools, particularly tools that generate an immense amount of heat such as soldering irons or electric kettles. During the study conducted in Fall 2017, it was important to consider the power requirements of soldering irons as the classroom had recently upgraded from smaller 30-watt handheld soldering irons to 750-watt soldering stations. When planning the Circuit Design and Soldering module, an initial class of 24 students arranged in

groups of two was planned for the module. As such, 12 soldering irons were computed resulting in the deficit of 16.60 amps as seen in Table 42.

*Table 42 – A power budget worksheet for the Circuit Design and Soldering maker module indicates that for a class size of 24, giving each group of two students a soldering station would exceed the classroom’s power capabilities.*

<b>Maker Module</b>	<i>Circuit Design and Soldering</i>							<b>Classroom Information</b>	
<b>Equipment</b>	<b>Voltage</b>	<b>Power</b>	<b>Current</b>	<b>Total Items</b>	<b>Amps</b>	<b>Total Items</b>	<b>Total Amps</b>	Class Size (Total Students)	24
	Volts	Watts	Amps	per Group	per Group	per Class	per Class	Students Per Group	2
Projector	120	432	3.60	0.1	0.30	1	3.60	Total Groups	12
Laptops	120	65	0.54	2.0	1.08	24	13.00	Circuit Rating (Amps)	20
Soldering Irons	120	750	6.25	1.0	6.25	12	75.00	Total Circuits	4
Fume Extractors	120	50	0.42	1.0	0.42	12	5.00	Total Circuit Capacity (Amps)	80
						<b>Total Amps</b>	96.60	<b>Load Remaining</b>	-16.60

Upon recognizing this deficit, alternative arrangements were considered, and the configuration detailed in Table 43 met both the curricular requirements of the module, as well as the classroom electrical capabilities. This was achieved by increasing the group size to three students which reduced the number of soldering irons required to eight. This resulted in an excess of available amperage to the classroom.

*Table 43 – A revised power budget worksheet for the Circuit Design and Soldering maker module shows the required electrical requirements are now within the limits of the classroom.*

<b>Maker Module</b>	<i>Circuit Design and Soldering</i>							<b>Classroom Information</b>	
<b>Equipment</b>	<b>Voltage</b>	<b>Power</b>	<b>Current</b>	<b>Total Items</b>	<b>Amps</b>	<b>Total Items</b>	<b>Total Amps</b>	Class Size (Total Students)	24
	Volts	Watts	Amps	per Group	per Group	per Class	per Class	Students Per Group	3
Projector	120	432	3.60	0.1	0.45	1	3.60	Total Groups	8
Laptops	120	65	0.54	3.0	1.63	24	13.00	Circuit Rating (Amps)	20
Soldering Irons	120	750	6.25	1.0	6.25	8	50.00	Total Circuits	4
Fume Extractors	120	50	0.42	1.5	0.63	12	5.00	Total Circuit Capacity (Amps)	80
						<b>Total Amps</b>	71.60	<b>Load Remaining</b>	8.40

In some cases, it may be determined that a particular maker module would be unsuitable for a classroom space and should therefore be relocated to an offsite space or workshop. This is particularly true for heavy duty, industrial, or specialty equipment such as full size industrial tools or equipment requiring high voltage. When computing the needs of the Traditional Materials maker module, a module that requires full size woodworking and metal working tools, it can be seen that a traditional classroom cannot reasonably support this type of work and would be better located to a space that can more reasonably accommodate this equipment (Table 44).

*Table 44 – A power budget worksheet for the Traditional Tools maker module shows a deficit of 125.63 amps as well as the need for 240-volt power, suggesting that this classroom space is incapable of accommodating this module.*

Maker Module	Traditional Materials - Woodworking and Metalworking							Classroom Information	
Equipment	Voltage	Power	Current	Total Items	Amps	Total Items	Total Amps	Class Size (Total Students)	24
	Volts	Watts	Amps	per Group	per Group	per Class	per Class	Students Per Group	3
Drill Press	120	180	1.50	0.3	0.38	2	3.00	Total Groups	8
Mitre Saw	120	1000	8.33	0.3	2.08	2	16.67	Circuit Rating (Amps)	20
Air Compressor	120	175	1.46	0.1	0.18	1	1.46	Total Circuits	4
Band Saw	120	320	2.67	0.3	0.67	2	5.33	Total Circuit Capacity (Amps)	80
MIG Welder	240	43000	179.17	0.1	22.40	1	179.17		
						<b>Total Amps</b>	205.63	<b>Load Remaining</b>	-125.63

Once the power demands of the maker modules have been matched with the capabilities of the classroom, it is also important to consider where that power will be accessed within the space. Within each implementation of the maker modules, each classroom was surveyed to determine how instructors and students would be able to access power for the various tools used during sessions. Among the five spaces, four distinct types of power access points were in use. They included standard wall outlets (often used in conjunction with power strips to expand the number of available

receptacles), ceiling-dropped outlets, floor-embedded outlets, and desk/table-mounted outlets (Figure 35). Each has a balance of strengths and weaknesses that were considered in providing power access during the modules.



*Figure 35 – Four types of power access points (left to right): Wall outlets with power strips, ceiling dropped outlets, floor outlets, and desk outlets.*

Wall outlets are extremely common in classrooms and were present in every one of the spaces surveyed for this work. They do, however, pose a significant challenge to conducting maker modules because in every instance, they lack sufficient proximity to where the students are working. While in some cases, such as Clough 102 and HackBerry, some groups can be positioned along walls to provide access, the necessary arrangements of students required some to be seated in the middle of the classroom without immediate access to these outlets. In both of these spaces, there were alternative outlets that could be used (floor outlets and desk/table outlets), but in some classrooms



these are not available. In situations where wall outlets are the only option, it is possible to route extension cords and power strips throughout the room, but this adds additional setup time to each module and care must be taken to cover the cords to avoid creating a tripping hazard.

Ceiling outlets are less common in traditional classroom spaces but can often be found in lab spaces where overhead infrastructure is exposed, making access to power from the ceiling more accessible. The advantage of this type of power access is that it allows outlets to be dropped directly over student workspaces without the need to run cords across the floor. In many cases the location of these drops can be repositioned, though doing so may require additional equipment such as a ladder, depending on the height of the ceiling. Finally, the outlets can slightly obstruct students' view around the room, however, the size of these outlets is generally negligible.

Floor outlets, if spaced frequently throughout a room, offer the greatest flexibility in designing a space in which maker-oriented curriculum can be taught. Such outlets are usually concealable which prevent creating a trip hazard when not in use. In Clough 102, the presence of these outlets allowed instructors to cluster tables around these access points and provided a nearly seamless solution. The primary drawback to these outlets is that they must be installed at the time of construction of a building as they are, in most cases, embedded directly into or under the flooring.

The final method of power access observed in classrooms is desk or table-mounted outlets. These access points provide the smallest distance required for plugging in tools, which can be advantageous with hand tools where the cords are generally only three to four feet in length. The close proximity of these outlets also allows students to

easily unplug tools when they are not in use. Two disadvantages to desk or table-mounted outlets is that the desks and tables they are attached to are generally immovable and are generally wired on the same circuit. Inasmuch that the desks/tables are favorably arranged, this is not an issue, as is was the case in HackBerry; however, in auditorium-style spaces such as Whitaker, this was more problematic. Where such desks are wired on the same circuit, it is possible to accidentally overload the capacity limits of the circuit.

*Table 45 – Power outlet availability among various classroom spaces at Georgia Tech and Berry College.*

<b>Campus</b>	<b>Building</b>	<b>Room</b>	<b>Wall</b>	<b>Ceiling</b>	<b>Floor</b>	<b>Desk/Table</b>
Georgia Tech	Clough	102	Yes	No	Yes	No
Georgia Tech	Whitaker	1214	Yes	No	No	Yes
Berry College	Green	203	Yes	No	No	No
Berry College	McAllister	PhyCo	Yes	Yes	No	No
Berry College	HackBerry	100/101	Yes	No	No	Yes

Throughout the implementations, the classrooms that provided the easiest access to power were generally those that provided a variety of options. In most cases, classrooms had more than one available type of access point, allowing for a variety of approaches to be taken. Green 203 was an exception and only had wall outlets available, making it generally unsuitable for maker-oriented activities and was abandoned after several weeks as noted in section 6.2.1.

#### 6.2.3.2 Equipment and Storage

The last physical consideration that presented a distinct challenge when implementing maker modules in classroom spaces was the proximity of equipment and the availability of storage space. Physical prototyping requires access to a reasonable number of tools and where these tools are located with respect to the classroom can



influence the overall structure of the class. Similarly, the presence of onsite storage must be considered as it shapes how an instructor prepares, presents, and concludes modules.

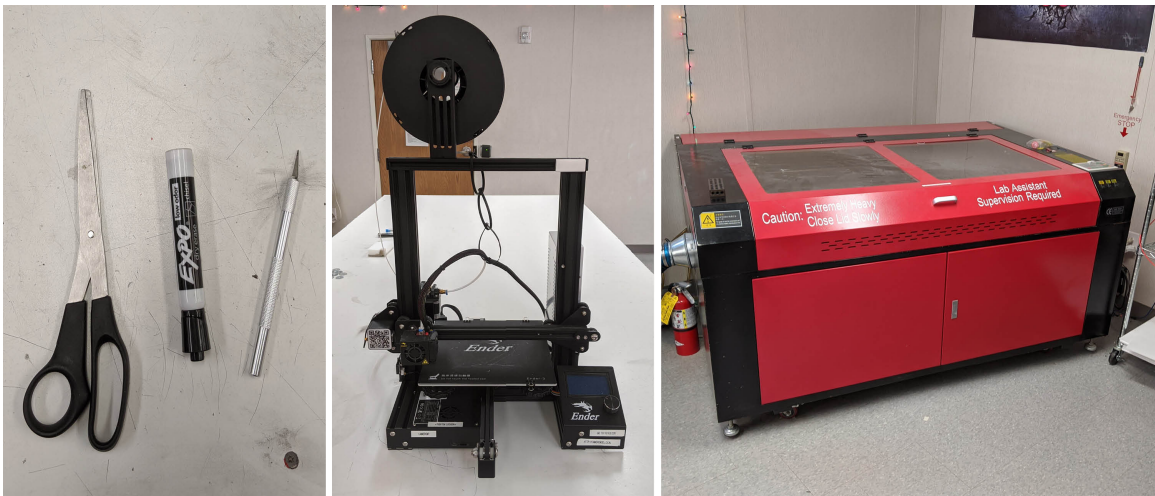
Like many of the previous practical considerations, the exclusivity of a classroom use for maker modules becomes an influence in how the space can be arranged and utilized for equipment and storage. When possible, there are a number of advantages to staging a room where equipment, tools, and storage are either within the classroom, or in close proximity to the classroom. While doing so may present some infrastructural considerations, immediate access to these resources allows instructors to more easily transition between elements of the maker module framework with minimal disruption. Where exclusive use of a classroom space cannot be acquired, arrangements must be made in order to either bring resources to the class on the day in which they are being used, relocate to other classroom facilities periodically throughout the semester, or a combination of the two.

*Table 46 – A survey of classroom equipment capabilities for maker modules indicates if tools and equipment was available in the classroom or in offsite facilities.*

<b>Classroom</b>	<b>Foam Board</b>	<b>2D Fab Design</b>	<b>3D Print Design</b>	<b>Wear Tech</b>	<b>Proto Arduino</b>	<b>Deconstr Tech</b>	<b>Trad Material</b>	<b>Circuit/ Solder</b>
Clough 102	Class	Class / Offsite	Class / Offsite	Class	Class	Class	N/A	N/A
Whitaker 1214	Class	Class / Offsite	Class / Offsite	Class	Class	Class	N/A	N/A
Green 203	Class	Offsite	Offsite	Offsite	Class	Class	Offsite	Offsite
PhysComp Lab	Class	Class	Class	Class	Class	Class	Offsite	Class
HackBerry Lab	Class	Class	Class	Class	Class	Class	Offsite	Class

A practical consideration of locating equipment in a classroom starts with a classification of the size of the equipment. Inspiration was taken from Weiser’s work in “The Computer for the 21st Century” in classifying technology devices in terms of inch, foot, and yard-sized increments [78]. Tools and equipment used in maker modules were

classified into one of these three categories based on their footprint – a combination of both the physical dimensions of the item, as well as its ability to be stored, moved, or stacked (Figure 36).



*Figure 36 – Different scale tools and equipment in maker modules. Small hand tools represent inch-scale tools, 3D printers represent foot-scale tools, and a laser cutter represents a yard-sized tool (left to right).*

Various small hand tools such as markers, X-Acto knives, and scissors were characterized as inch-scale tools and are generally easy to store a full class set in a single small shoebox-sized plastic container (~350 cubic inches) that can easily be stacked for storage or transportation. Desktop equipment such as 3D printers, soldering stations, and electric kettles fit the description of foot-scale tools and generally require roughly a 12x12 inch area on a desk. These items can be moved with some effort and most are able to fit in larger trunk-sized storage containers (~4,000 cubic inches). A large amount of variability was found among tools and materials that were classified as yard-scale. These items generally require a significantly larger footprint when stored and can be

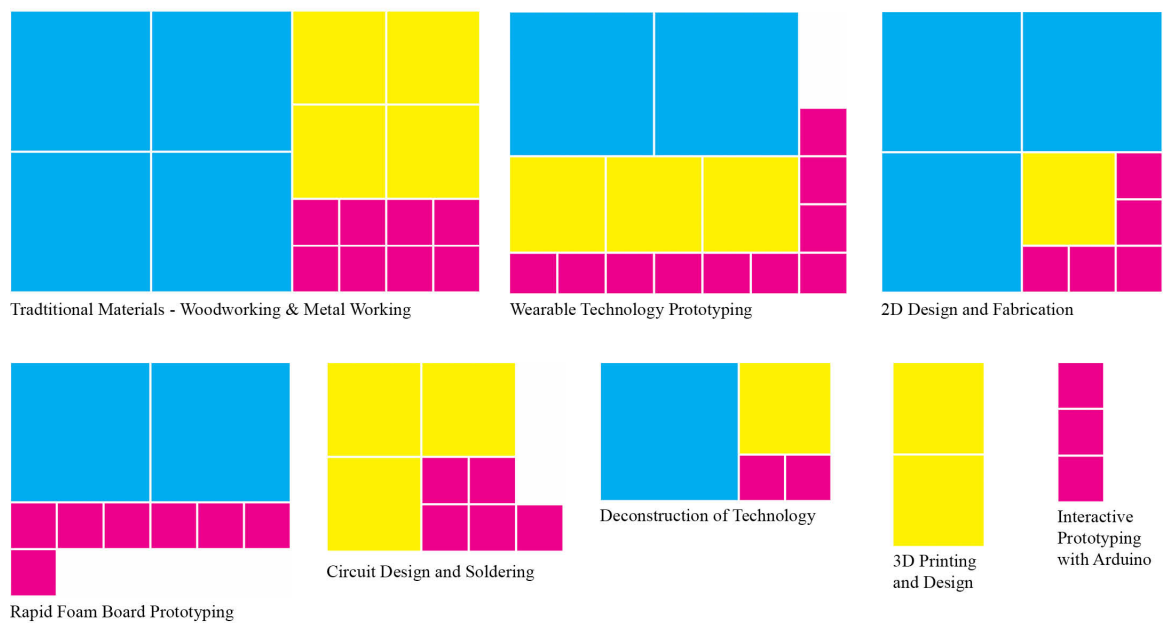
cumbersome if not impossible to move. Such items range from oversized cutting mats and foam board to laser cutters and vinyl cutters. While cutting mats and foam board are relatively light and extremely stackable, making it possible to transport them, yard-scale industrial equipment generally cannot be moved without significant time spent transporting, setting up, and calibrating the equipment. Because of this, such yard-scale equipment is better located permanently within a classroom space or used offsite when required.

*Table 47 – Classifying tools and materials used during the Wearable Technology Prototyping maker module using inch, foot, and yard classifications.*

<b>Wearable Technology Prototyping</b>	<b>Size Classification</b>		
<i>Tool</i>	<i>Inch</i>	<i>Foot</i>	<i>Yard</i>
Foam Board			x
Cutting Mat			x
X-Acto Knife	x		
Hot Glue Guns	x		
Markers	x		
Rulers		x	
Thermoplastic	x		
Mugs	x		
Electric Kettles		x	
Velcro	x		
Hot Wire Cutters		x	
Scales	x		
Weights	x		
Tape	x		
First Aid Kit	x		

In order to assist with estimating the footprint required for the maker modules within a classroom space, the equipment required for each module was listed and classified using the inch/foot/yard method (Table 47). A simple graphic visualization was then created to demonstrate the overall physical impact each module can have. Items that are classified as inch-scale are visualized using 1x1 unit squares, foot-scale items using 2x2 unit squares, and yard-scale using 3x3 unit squares. While these graphical units do

not represent the literal dimensions of the equipment, they are helpful in understanding how some modules are more resource-heavy than others and may assist in determining which modules may be appropriate for a given classroom space. For example, in Figure 37, modules along the top row require a significant amount of space to host the tools and materials required. In the most extreme case, the Traditional Materials module required offsite instruction because the required footprint for this module exceeded the capabilities of any of the classrooms in which modules were conducted. Modules along the bottom row of Figure 37, however, would be easier to conduct in the classrooms studied in this work.



*Figure 37 – A graphical comparison of the equipment and material footprints for each of the eight maker modules ranked from most intensive (upper left) to least intensive (lower right).*

### **6.3 Kit Development to Support a Variety of Maker Module Activities**

As hands-on building activities find their way into traditional computer science and engineering curriculum through physical computing, ubiquitous computing and prototyping classes, kits have become a common way to support the demands of providing tools and materials to students [79]. Within this context, kits are a thoughtful and organized collection of items that support a specific hands-on making activity.

Throughout the numerous iterations of conducting the maker modules, the development of kit strategies has emerged as a way to practically coordinate the various tools and materials required by the modules with the goal of reducing the amount of time preparing and distributing the materials during a class session. In addition to the practical preparations of the materials, how kits are organized can also influence the way in which students constructively think about the learning goals associated with the maker modules by adding or removing creative constraints through the way in which the materials are presented to the students.

#### *6.3.1 Traditional Kits*

The most common approach to supplying kits of tools and supplies to students is to create or purchase kits that contain an identical number and variety of components to be distributed to individual students or groups. The Sparkfun Inventor's Kit, for example, contains simple electronic components that allow students to work through 16 different exercises to learn basic electronic programming and physical prototyping skills [80]. While the scope of this kit is rather broad, others have created kits to narrow on specific topics such as wearable computing, e.g. LillyPad Arduino kits [81]. The appeal of such

kits often comes from their relative accessibility to students that are new to prototyping and their pre-packaged format. In this work, such standardized collections of tools and materials will be considered traditional kits. These traditional kits are characterized by an individual container for each student or group that has all the required tools and materials for the activity (Figure 38).



*Figure 38 – A traditional kit approach provides an equal number of tools and materials to each student or group.*

Traditional kits serve a practical purpose when conducting resource-intensive maker modules in a classroom environment, although these kits can pose some challenges with respect to their preparation. Because traditional kits are organized around a set number of tools and materials that are placed in a box and given to a student or group, there is an implied understanding between the instructor and students that the inclusion of those items are intentional. The intentional organization creates a natural logical constraint that can result in students thinking that everything in the kit must be used and any leftover parts or components may be the result of having made a mistake [26]. This constraint can be leveraged to help students develop their skills with unfamiliar

tools or techniques because there are inherently fewer creative choices that they are allowed to make through this constraint. This convergent approach is particularly useful in maker modules that are designed to develop primary skills that will be used in later modules or are a critical component of a significant semester-long project or assignment in the course.

When implementing traditional kits into classrooms, there is an underlying benefit for the instructor in that there is a large amount of control in knowing the exact types and quantities of tools and materials each kit contains. This can make objective assessment of how each student has utilized their kits more straightforward. Furthermore, the amount of time spent by students in class getting access to the materials is reduced because the kits provide immediate proximal access to everything required for the maker module. This immediate access also accelerates clean up time at the end of an activity because students are able to quickly return tools and materials to the kit in their area. This reduced time in class comes with a trade-off in pre-class preparation as each kit must be created or inspected to ensure that each has the required number and type of materials needed for the activity. This preparation time occurs both when creating traditional kits for the first time, or when restocking consumable materials from previously used kits.

### *6.3.2 Workbench Kits*

Beyond traditional kits, however, there exist other approaches for supplying tools and materials to students that can often reshape their learning experience and produce alternative outcomes. For example, in Perner-Wilson's "kit of no parts," students expand their conceptual knowledge of electronics by using available crafting materials to create

simple sensors [82]. This alternative approach has the potential to augment students' understanding of components beyond a traditional kit in some circumstances. Another approach, commonly used in supplying tools and materials to students involves pooling all of the class resources into categorized bins that allow students to explore, select and share components throughout the entire space. This workbench kit, so named because it resembles a workspace where tools and materials are communally available, contrasts from the traditional kit because students must now make choices with respect to a wider variety of components to choose from (Figure 39). Using this approach may also help students as they transition from in-class activities to independent out-of-class activities in a prototyping lab or workshop space because of the similar arrangement of tools.



*Figure 39 – A workbench kit groups similar tools and materials together in a central location and allows students or groups to choose what they would like to use.*

The lack of a strictly ordered traditional kit allows students to make conscious choices about what materials may best support their creative concept. It removes the logical constraint present in traditional kits in that the tools and materials are placed in a “buffet-style” arrangement that gives students the freedom to sample a bit of everything



or focus their attention on a smaller subset of available tools or materials. This lack of constraints allows students to think more divergently about their overall design goal and can indicate understanding of the underlying concepts in the maker modules rather than just technical competency with a tool. As such, this approach can be useful in later modules where an instructor is evaluating students' overall understanding of course content.

In the workbench model, the centralization of classroom resources can be organizationally disruptive. The non-proximal access to resources means students will have to leave their seats in order to procure tools and materials, and in many cases will have to make repeat trips. Because of this, some classroom types are more conducive to this model than others. For example, the traditional classroom setup of Clough 102 provided ample space for students to move around, whereas the tiered auditorium seating of Whitaker 1214 made using workbench kits very inefficient. Furthermore, allowing students to serve themselves, can create literal shortages of certain tools and materials. In terms of preparation, however, the workbench kit is generally more efficient than traditional kits for two reasons. First, the spaces from which tools and materials were borrowed already organized resources in this manner, meaning that they could be transported as-is. Second, inventorying and replenishing consumable materials from kits was easy because it was trivial to check the supply of each material by looking in its respective container. This efficiency, however, is counterbalanced by an increased amount of time spent cleaning up after a class session because students have to leave their seats to return all the tools and materials to the workbench kit table.



*Figure 40 – Workbench kits can be more efficient to prepare because many spaces organize tools and materials this way, such as simple hand tools like hot glue guns, glue sticks, and makers (left) or even soldering workstations (right).*

### 6.3.3 Results

Traditional and workbench kits can facilitate learning opportunities for students and can make classroom instruction easier for instructors if designed well. Throughout the development of maker modules, traditional kits and workbench kits emerged as practical ways to supply students with the tools and materials needed to engage in hands-on maker-oriented activities. As these approaches were used in classrooms, the strengths and weaknesses of each approach was determined through observation as well as through post-course interviews with students.

*Table 48 – Kit types developed for each of the maker modules.*

<b>Maker Module</b>	<b>Kit Type</b>
Rapid Foam Board Prototyping	Traditional Kit
2D Design and Fabrication	Workbench Kit
3D Printing and Design	Traditional Kit
Wearable Technology	Workbench Kit
Interactive Design with Arduino	Traditional Kit
Deconstruction of Technology	Traditional Kit
Traditional Materials	Workbench/Traditional Kit
Circuit Design and Soldering	Traditional Kit

Each iteration of implementing a kit strategy in a maker module helped form a list of characteristics that uniquely defined the traditional and workbench models. These characteristics can be helpful when determining which model to use with respect to the overall learning outcomes of the maker module as well as the constraints imposed by classrooms as discussed in section 6.2. These characteristics include workflow, preparation, proximity, equity, and clean-up (Table 49).

*Table 49 – A comparison of characteristics for traditional and workbench kits.*

<b>Kit Type</b>	<b>Workflow</b>	<b>Equity</b>	<b>Preparation</b>	<b>Proximity</b>	<b>Clean-Up</b>
Traditional	Resource – Concept	Yes	Slow	Immediate	Fast
Workbench	Concept - Resource	No	Fast	Distant	Slow

*Workflow* refers to the divergent and convergent constraints discussed in the description of the traditional and workbench kits. It infers that the organization and presentation of the materials themselves can influence and shape the approach that students use during the development of prototypes in the maker modules. The constrained convergent effect of traditional kits creates a workflow of students thinking primarily about the tools and materials that are provided to them, and then secondarily about what artifact they can create from them that fits the parameters of the maker module (resource-

concept workflow). During interviews, many students indicated that the constrained nature of the traditional kits influenced their design thinking. For example, when asked about the role traditional kits had during the Rapid Foam Board Prototyping module during the UID-F15 course, students responded:

*We were trying to make good with what we had, we were trying to think of what we can make with foam core. (UID-F15).*

*You make your design based on what you're given. You form your ideas on that we've been given this and what can we do with it. (UID-F15).*

This shows the impact that the creative constraint inherent to traditional kits can have. This constraint showed to be helpful when trying to help student focus their ideas while learning new skills or concepts. Responses from students in the MUC-S16 course the following semester showed a similar attitude as students from fall 2015. One student provided this insight regarding the benefits of constraining creativity with traditional kits:

*Because if you think of lamp and you think all the technologies out there. What can we create? There are so many more possibilities. If you're just looking at the foam core, you're like, "All right. What physical, tangible thing can we create, and how do we present it to the class?" So, it kind of hindered us that way in our thinking. But it definitely helped us, because like I said, people don't like options. If we had all the options, it would be too hard to come up with one idea. Since*

*we're getting these tangible objects, we're like, "Okay. Well, we know we can build a base. We know we can build a pole to put this on. We know we can build a bulb. We know we can build wheels." That's how we kind of developed our ideas. (MUC-S16).*

The divergent effect of workbench kits contrasts traditional kits in that the diverse choice of materials and tools allows them to structure their workflow around developing a concept that fits the maker module parameters, and then identify tools and resources that will help them fabricate that concept (concept-resource workflow). This approach was employed in modules where students already had some previous experience with the physical fabrication skills and were working on demonstrating a concept with them, such as during the Wearable Prototyping module. One student contrasted the two approaches in this way:

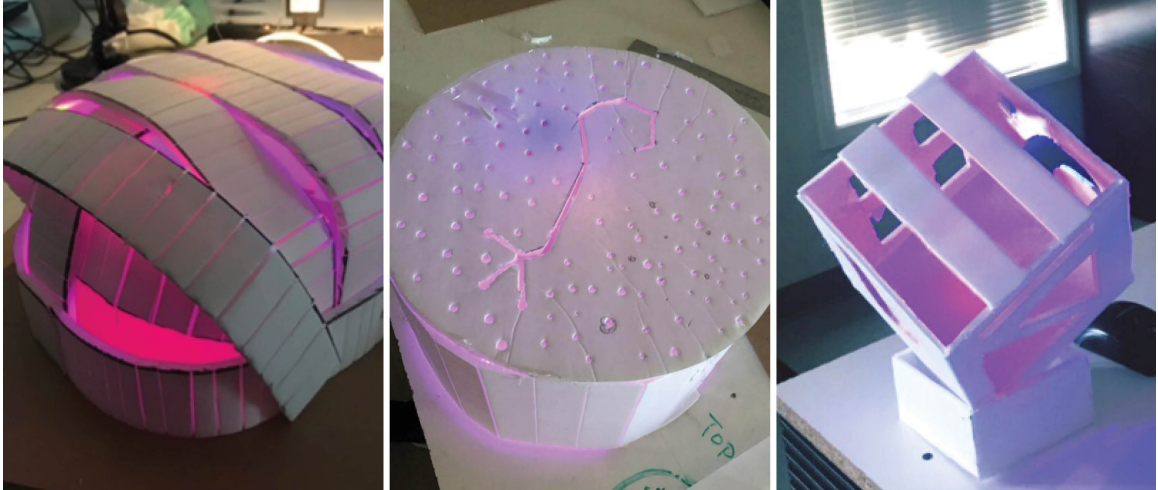
*Having them all in a spot, like everything in one spot usually meant that there were more types of tools, which was nice because it allowed a little bit more flexibility in what you could build. But having them all delivered to the table kind of got you thinking a little bit more about what you could build. Because there are a limited number of things you can do with the tools you're given, if there are no other tools then you kind of have to work with what you have. But if you start without the idea of what tools you have, you tend to be a little more creative in what you can build, but then you're limited in terms of what you can find. (MUC-S15).*

The flexibility during the workbench kit model occurred when the resources were “all in a spot” and gave students more creative freedom to develop a concept and then find the tools necessary to fabricate it, even if there were still limitations in what resources were available.

The difference between these two approaches can help an instructor determine which kit may better fit the learning goals associated with a particular module. As seen in Table 48, modules that introduced new tools and techniques such as prototyping with foam board, 3D printing, Arduino programming, and soldering, used the traditional kit approach to help students better focus on developing those skills in a constrained environment. Whereas modules that used previously learned skills and focused on extensions of those skills to demonstrate content knowledge utilized a workbench kit approach. These modules include the 2D design and wearable technology modules where students are revisiting skills from previous modules but applying them to a specific context. One notable exception to this pattern, however, is the traditional materials module. In this maker module students are learning to work with traditional woodworking and metal working tools which would imply that a traditional kit approach should be used. However, a hybrid traditional/workbench approach was used. The scale of the equipment and the limited quantities of tools precludes the possibility of giving each student group their own set to work with, thus a pure traditional kit model was not possible, and a workbench-style setup was used instead. However, because for many students this was their first time using such tools, the primary focus in this module is skills building and they are required to build a simple model using precise specifications

with no allowable creative deviations. Thus, while the tools were organized using a workbench-model, access to the tools was traditional because student groups were allowed to use the tools one at a time.

The *equity* characteristic of traditional and workbench kits refers to students' equal access to tools and materials. Like the workflow characteristic, this feature can be a reflection on the underlying learning goals associated with the maker module. In traditional kits, there is perfect equity because each group has the exact same type and number of tools. In workbench kits, however, while students have an equal opportunity to select from a variety of tools, inevitably, it is unlikely that every group will select the exact types and quantities of tools for the creation of their prototypes. The difference in these approaches is apparent from the types of artifacts created during the Rapid Foam Board Prototyping module (traditional kit) and the Wearable Technology module (workbench kit). In the Rapid Foam Board Prototyping module, student groups were each given the same number of hot glue guns, glue sticks, X-Acto knives, and foam board. Because the focus of this activity was to help students learn the physical skills necessary to create rapid paper prototypes, the material constraints result in a similar utilization of materials (Figure 41).



*Figure 41 – Three lamps from the Rapid Foam Board Prototyping module show a similar utilization of resources constrained by the traditional kit approach.*

The inequity of the workbench kit approach is very apparent in the Wearable Technology module, as students are provided with many more choices with what materials or tools will best support their concept. As seen in Figure 42, students took a variety of approaches to creating wearable devices with some opting to exclusively use foam board (left), thermoplastic (right), or a combination of the two (center). Even the methods for creating bands (waistbands and wristbands) were approached differently by various student groups.





*Figure 42 – Three wearable devices show a diverse selection of material choices and prototyping approaches from the workbench kit approach.*

When interviewed about resource availability during the Wearable Prototyping module, students identified that having open access to some or all of the tools and materials created scenarios in which some items may not be available. One student noted that this caused their group to think spontaneously about what resources were left and how they could be used to achieve the overall design goals of the module:

*You could pick and choose what you wanted. You could use some items that other people didn't use or find a different way to use those items. You had freedom, I guess, on both aspects. But you were also limited. If you needed something different and weren't able to get that, you had to work with what you had. So, you had to think of it on the fly. (MUC-S15).*

*Preparation, proximity, and clean up* are largely functions of the physical classroom and time constraints that should be considered when deciding which approach

to implement for a module. The amount of time required to prepare the kits is relatively high for traditional kits because it is necessary to parse out tools and materials equitably among the various containers that will be distributed to student groups. The workbench model generally negates this process because most of the resources are already arranged in this fashion and the only step that needs to be taken is ensuring that there is an ample supply of each resource. Within the classroom space, students' proximity to the materials should be considered with respect to the ability for students to easily move around the space. Where there is sufficient space, instructors have the freedom to locate the materials in the immediate vicinity of students (traditional kit) or distantly (workbench kit). In auditorium-style classrooms, however, distantly-placed resources will generally create time inefficiencies in the class and may disrupt the overall flow of the modules. It should be noted that issues can arise even in large open classroom spaces. During the first offering of maker modules during MUS-S15, a student made the following observation comparing having immediate access to resources in traditional kits versus having to go to a centrally-located workbench kit:

*If we were given a toolbox, it was much easier, because all we had to do was pick up one toolbox and walk over to our thing and start working. I liked the toolbox better because it's just like one box plus whatever paper or whatever needed to be taken, and also any dangerous tools were all in the toolboxes. So, there was no way of you cutting yourself when you're handling those tools. (MUC-S15).*

As can be in this first part of the student's observation, the traditional kit required little effort or time to get started on work, as well as provided an element of safety because students didn't have to sort through a large box of tools to retrieve what they need—in this particular case, X-Acto knives. The same student went on to explain an experience with workbench kits during another module:

*But with items, it was harder, because it depended on the size of the items, too. If it was a big poster board, two of us might have to go up there to grab everything because the other person might have trouble balancing all the tools at one time and walking over. Or we'd have to make multiple trips up just to get the same supplies as everybody else. I mean, in a way I also liked the fact that we could just go grab what we needed, because that prevented us from taking more than we wanted for that particular assignment. (MUC-S15).*

In this observation it can be seen that this module required multiple trips to the workbench because of the size and number of materials the group required for their project. Interestingly, the student did note that this approach minimized waste because they only took the amount they needed (with an option to return for more) as opposed feeling compelled to use what may have been assigned to them in a traditional kit model. The student then concluded their remarks with an understanding that different modules were intentionally implemented with different kit strategies:

*I think it depends on what the assignment was that day, for sure. (MUC-S15).*

Finally, the efficiencies of clean-up with either kit approach was found to be inversely proportional to the preparation characteristic. Whereas traditional kits take longer to setup, clean-up of these kits is relatively quick because students are able to return all tools and materials immediately to the storage containers that are located at their workspaces. Workbench kits, however, are easy to setup, but take a longer time for students to return and sort all of their tools and materials into the centrally located storage containers. Thus, the time allotted for each module and the classroom in which it will take place can influence the decision to use traditional or workbench-style kits as affected by the preparation, proximity, and clean-up characteristics.

#### **6.4 Discussion**

One of the most difficult parts of implementing maker-oriented learning into a classroom is dramatically changing the nature of how learning is structured in physical spaces that may not have been designed for hands-on activities. Because of this, the contributions made in this chapter are the fundamental considerations that should be made when preparing to implement the maker modules into a course's curriculum. These contributions span three distinct areas as detailed in the previous sections. They include how to structure class sessions with respect to class duration and frequency of meeting, physical space considerations, and kit development for the tools and materials used during maker modules.

In this work, a number of class scheduling schemes were experimented. Some of these schemes were mandated by the administration as a result of using classroom spaces

that had to serve the demands of several other classes. In spaces where the instructor had more control over the schedule, I was able to tightly control the amount of time the class met each session, as well as how many sessions per week were conducted. From this, I was able to create guidelines for each maker module that details the amount of time courses should meet for this type of maker-oriented learning to occur.

With respect to the physical space considerations, there are quite a number of contributions made, because this was one of the largest obstacles to overcome when incorporating maker modules into a classroom. The first contribution is a method for evaluating the appropriateness of a classroom space for maker-oriented activities through the calculation of overall classroom square footage with respect to the overall class size. This method takes into account the size of work surfaces as well as the arrangement of the space and makes recommendations through a direct comparison among several spaces in which modules were implemented. Furthermore, an analysis of artful surfaces in classrooms was made to demonstrate the role that they play in helping students take creative concepts in their minds and transition them into physical prototypes. Also, a guide was contributed in this chapter that allow instructors to reasonably assess the power requirements of each module given the electrical capabilities of the classroom in relation to overall class size and individual group size. Finally, a visualization that helps instructors and facilities personnel understand the physical footprint of tools and equipment was developed to assist in locating these resources on a university campus.

The final contribution in this chapter addresses the challenges of delivering tools and materials to students during a maker module session. Thus, the concept of traditional and workbench-style kits was developed to assist instructors in understanding the

strengths and weaknesses of each approach and when each style may be appropriate given the overall makeup of the class and the desired learning outcomes in each maker module. By implementing these kit strategies, instructors can mitigate inefficiencies in preparation and cleanup, as well as shape how students are approaching the creative activities in the maker modules.

## **6.5 Conclusion**

Throughout this chapter I explored a variety of approaches to answering the research question “*What considerations and practices are necessary when implementing maker modules in a traditional classroom and curriculum?*” The guidelines and worksheets developed as a result of this exploration have broad application to instructors and administrators seeking to implement maker-oriented learning into their programs and curricula as it allows them to make fundamental assessments to both the makeup of their courses with respect to scheduling and class size, but also to the physical infrastructure and equipment that is available to the program and university. As such, the contributions detailed in this chapter can help guide these programs to understand their current state of readiness for such an approach, as well as assist in further development and construction of physical spaces where this type of instruction can occur if such a space does not currently exist.

If adhered to, these guides also serve as a point to help ensure that the maker-oriented activities can occur with as few disruptions to the instructors and students as possible. In many cases, the implementation of the maker modules may be the first time either instructor or students have engaged with these types of activities, and thus it is

important to minimize the number of technological issues that may arise. The practical implementations developed in this chapter often times came as a direct result of exactly those types of failures, whether it be accommodating a large number of students, or tripping fuses in a classroom. Thus, the lessons learned and materials created to address such issues can ensure a more cohesive experience for those implementing maker-oriented learning experiences in the future.

## CHAPTER 7. CONCLUSION

Throughout this work, a model for creating and implementing maker-oriented activities in human-centered design and human-computer interaction courses in undergraduate and graduate programs has been developed, implemented, and tested. This process resulted in answering three fundamental questions that will allow instructors to more easily and effectively implement maker-oriented activities in their classrooms.

### 7.1 Maker Module Framework Conclusions and Contributions

The first question addressed in this work was “*What are the elements that should be considered when developing a framework for maker modules in human-computer interaction courses?*” In this framework, five distinct elements are described that provide a foundational structure upon which instructors can develop maker-oriented modules that will allow students to participate in hands-on physical prototyping activities that address core concepts and learning goals in the classes in which they are conducted. These elements include setting out *expectations* for the modules, delivering *exposition* to help students understand the underlying course concepts, facilitating *exploration* to assist students in developing prototyping skills and connecting them to abstract concepts, conducting *explanation* sessions where students are able to present their work and receive feedback and critique, and finally, *expansion*, whereby students can extend their in-class experiences to other course- or industry-related contexts.



The creation of this framework represents a significant contribution through which maker-oriented learning can be developed for human-computer interaction courses. By enabling instructors to connect broad learning objectives to specific elements of maker-oriented instruction, they can cohesively structure hands-on activities in their courses that empower students to explore course concepts in a new and unique way.

## **7.2 Holistic Maker Module Curriculum Conclusions and Contributions**

The second question addressed is “*What does a holistic curriculum of maker modules consist of?*” To answer this question, I described a set of eight distinct maker modules that follow the previously established maker module framework and detailed the iterative approach through which these modules were developed and adapted through data gathered from student interviews, instructor feedback, and observations that I made. These modules have contributed to the area of maker-oriented learning in that they have since been implemented in a variety of human-centered design and human-computer interaction courses by faculty where they continue to be a core component of the curriculum in those programs.

In addition to the development of these eight maker modules, the description of iteratively developing the foam board module provides a template through which new modules can be created by instructors wishing to include maker-oriented learning activities into their courses. This ability is made possible through showing how the modules were adapted overtime to meet the evolving interests of students, as well as implementing new and emerging technologies into the curriculum.

### **7.3 Considerations and Practices Conclusions and Contributions**

Finally, this work addressed the final research question “*What considerations and practices are necessary when implementing maker modules in a traditional classroom and curriculum?*” The answer to this final question was necessary provides instructors with a set of fundamental guidelines that allow them to assess a classroom space and available infrastructural resources and adapt the maker module activities around the course and classroom capabilities. These capabilities include how class time and schedules can be structured, physical space considerations such as classroom furniture, artful surface, electrical power and equipment, as well as how to arrange tools and materials in kits to better address the learning goals of individual maker modules. Through these recommendations, instructors are able to better anticipate and overcome challenges in order to more seamlessly incorporate the modules into their class sessions.

These considerations and recommendations were then compiled into a series of guides and protocols through which they can specifically address the strengths and weaknesses of the physical resources available to them. Furthermore, this contribution can assist instructors in exploring the physical requirements necessary if they wish to accommodate growing class sizes or develop new facilities for conducting maker-oriented instruction.

### **7.4 Future Work**

Throughout the development of this work, a number of future opportunities have arisen that warrant further exploration. One of the largest contributions made in this work has been the development of a cohesive collection of maker modules that can be used in

the creation of an HCI course that is focused on the principles of rapid prototyping physical artifacts. As such, it would be logical to continue to refine these works with additional topics to create a textbook and instructor manual that can supplement such courses. An example chapter of such a textbook is included in Appendix F of this work. The creation of an instructor manual would be of particular importance given the relative unfamiliarity that may exist among HCI faculty with the wide variety of prototyping topics discussed in this work as well. The instructor manual would serve as a primer through which instructors can utilize a variety of the instruments developed in this work (power requirements calculator, classroom space evaluation, etc.), in addition to providing additional context for how a maker-oriented approach can enrich traditional approaches to teaching HCI courses.

In addition to these resources that are directed toward the creation of a single class, there also exists an opportunity to expand and develop this maker-oriented approach to an entire program's curriculum. Within this work, the classroom interventions were constrained to three specific courses, with little consideration given to how this approach may influence subsequent courses that students may be taken. However, given the ongoing development of the Creative Technologies program at Berry College, there is an opportunity to implement the maker module framework and methods for evaluating cohesion between modules and learning objectives in the other courses being taught. The ongoing development of this program and implementation of this approach broadly across the entire program may result in the development of a more cohesive curriculum where the elements learned in each course are informed from previous courses and serve to prepare students for future courses. Furthermore, as

Creative Technologies program matures, it may serve as a template for other institutions looking to adopt similar strategies into their own programs.

## **7.5 Summary**

In conclusion, this work has established a pattern and method through which maker-oriented activities can be developed more efficiently to meet the learning goals of the courses in which they are presented. It has furthermore proposed specific modules which can be implemented in a variety of courses and how those modules can be adapted over time to better address the needs of the course, its students, and its instructor. Lastly, it has developed and presented simple guidelines that will help determine the overall feasibility of implementing such activities in traditional classrooms. Through this work, such maker-oriented learning approaches can continue to take hold and flourish in human-centered design and human-computer interaction courses.

## **APPENDIX A. GEORGIA TECH MAKER-ORIENTED LEARNING**

### **INTERVIEW GUIDE**

#### **INTRODUCTION**

- What did you think of the class?
- Was this class different than other classes you have taken? (How?)
- What were your expectations in taking the course? (And were they met?)
- What skills did you come in the class with that helped you? What skills did you need the most help on?

#### **TRANSFER**

- Is there anything you learned in this class that might benefit you in your career?  
(If yes, what is it? If no, why?)
- Did you get any new ideas or new projects based on what you learned in this class? (If yes, what?)
- Is there anything you learned in this class that helped you understand something outside of this class? (from another class or hobby perhaps)
- Were there any in-class activities that helped you with your final project? (Which one, how?)

#### **REFLECTION**

Critiques

- What did you think about the critiques?
- What did you think about the feedback from your peers?
- Did you learn anything from participating in other people's critiques? (can you give an example)
- What did you think about the critiques from outside visitor/faculty?
- How do critiques compare with the lectures in class?

#### Hands on activities

- What did you think about the hands-on in-class activities?
- How do you think these activities compare to lectures in class?

#### Three-hour class period

- What did you think of the three-hour class?
- How did it compare to other classes? (three one-hour lectures, 1.5 hour two days a week, classes with a lab)

### COMMUNITY OF LEARNERS

#### General

- Did you meet any new students in this class?
- Did you work on any of the courses or projects outside the class with the new people you met?
- Do you think you'll keep in touch with those people?
- Did you meet people from outside of your majors?

- Did you know anybody in this class before this semester started and did you get a chance to work with them in this class?

#### In-class activities

- Tell me about one time you had to work in a group during an in-class activity.
- Tell me about one time you helped someone. (Whom, what did you help with?)
- Did you ever get help from your peers? Tell me about that.

#### Group project

- What was it like working in a group?
- Were there any cases where you knew the most or least in a group? How did it change your experience?
- Did you learn things from other people on your team?
- Did you think other people on your team learned from you?
- Do you think you are a leader? Is there a part of the project you owned?
- Do you see anything unique other team members brought to the project?

#### SPACE USE

##### Classroom

- Is this classroom different than other classrooms? (How?)
- What aspects of the classroom were the most useful during the in-class making activities?

- What aspects of the classroom were most challenging to work with? (Enough space?)
- Did you rearrange any of the furniture in the space to make it easier for you to work? (How, Why not?)
- How did the arrangement of the room affect your interaction with other people?
- How well did the space work for critiques?
- Is there anything you would change about the classroom?

#### Prototyping space

- As you worked on your group project, where did you spend time on your project? Where did you brainstorm with your group? Where did you code? Where did you build physical objects?
- What spaces did you find the most helpful? (Prototyping Lab at GVU, Invention Studio, Industrial Design Studio, Personal Space, Libraries, Other?)
- Why did you choose those spaces?

#### TOOLS & MATERIALS

##### In-Class Activities

(Throughout the in-class activities we provided tools and materials to you in two separate ways. Sometimes we provided all the materials in a box kit and other times we put all the available materials on a table and allowed you to select whatever you needed.)

- What was good about these arrangements?
- What were the challenges?



- What did you think was the most fun, interesting tool that we provided?
- Was there any that was hard to use? Did you hurt yourself with them?
- Was there anything you wished you would have had?

#### Out of Class Activities

- What tools and materials did you use to work on your group project?
- Did you buy any tools or materials to help you make your project?
- Is there any in-class activity that we could have done to help you with your final project?

#### Sparkfun Inventor's Kit (Arduino Kit)

(At the beginning of the semester, each member of the class was given a Sparkfun Inventor's Kit that included an Arduino and variety of sensors and actuators, as well as an instruction book with sample circuits and code.)

- What were the most common components used in your Arduino kit?
- What was missing that you wish that you had?
- What about the sample circuits and code was useful? What would you change about it?
- The kits are \$100, would buy it yourself, after having used the kits? (Would you pay for it, if it is \$50? If not, why?)
- Now that you own the kit, would you use it again?
- Would you have rather gone to a shop?
- Did the toolkit encourage you to think about other tools you could use?

## APPENDIX B. COURSE ABBREVIATION GUIDE

Abbreviation	Course Name	Institution	Semester	Year
MUC-S15	Mobile and Ubiquitous Computing	Georgia Tech	Spring	2015
UID-F15	User Interface Design	Georgia Tech	Fall	2015
ITP-F15	Introduction to Prototyping	Berry College	Fall	2015
MUC-S16	Mobile and Ubiquitous Computing	Georgia Tech	Spring	2016
ITP-S16	Introduction to Prototyping	Berry College	Spring	2016
UID-F16	User Interface Design	Georgia Tech	Fall	2016
ITP-F16	Introduction to Prototyping	Berry College	Fall	2016
ITP-S17	Introduction to Prototyping	Berry College	Spring	2017
ITP-F17	Introduction to Prototyping	Berry College	Fall	2017
ITP-S18	Introduction to Prototyping	Berry College	Spring	2017

## APPENDIX C. BERRY COLLEGE COURSE EVALUATION

**Section 1** - Evaluate the following statements using the following criteria: (1) Strongly Disagree (2) Disagree (3) Neither Agree nor Disagree (4) Agree (5) Strongly Agree

*Question 1* - The graded work in this course (e.g., exams and papers) was consistent with the content of the course that was presented (e.g., textbooks, in-class activities, and lectures).

*Question 2* - Overall this was a valuable course.

**Section 2** - Please consider how much you have learned in this course. This includes the concepts covered in the class and any professional skills that are associated with this area of study. Evaluate the following statements using the following criteria: (1) I made no significant gains in my understanding (2) I made very few significant gains in my understanding (3) I made a few significant gains in my understanding (4) I made significant gains in my understanding (5) I made many significant gains in my understanding

*Question 3* - To what extent do you feel that you made significant gains in your understanding of the concepts explored in this class?

*Question 4* - To what extent did you make significant gains in your intellectual development? This might include critically reading, critically thinking about issues raised in class, identifying patterns in data, writing documents, lab skills, or working with others.

**Section 3** – Please answer the following questions.

*Question 5* - As best you can, please estimate the average number of hours per week that you spent doing work for this class outside the classroom. This would include reading, studying, writing, or any other activity relevant to the class.

*Question 6* - Please describe the strengths of this course and the instructor(s). Try to be specific and give examples (e.g., textbook and other course materials, classroom activities, evaluations).

*Question 7* - What recommendations would you suggest for improving this course and/or instruction?

## **APPENDIX D. CREATIVE TECHNOLOGIES IMPACT SURVEY**

### **Section 1 – Background Information**

- Gender
- Age
- Ethnicity
- Current Class Standing

### **Section 2 – Formal Experience in High School**

- How many AP (Advanced Placement) classes did you complete in high school?
- What was the highest level of mathematics you completed in high school?
- What was the last science class that you completed in high school?
- Did you take a physics class in high school?
- Did you take a computer science class in high school?
- Did you take an engineering class in high school?
- Did you ever use physical prototyping technologies in these classes?
  - Prototyping technologies include paper prototyping, 3D printers, laser cutters, Arduino, electronics, etc.
  - If you answered yes to the question above, what prototyping technologies did you use?
- Prior to entering college, how would you rate your capabilities in the following areas?
  - Mathematics
  - Engineering
  - Physics
  - Computer Science
  - Business
  - Art
  - Music
  - Writing
  - Electronics
  - Programming
  - Woodworking
  - Robotics
  - Design

### **Section 3 – Informal Experience in High School**

- Please describe any activities that interested you in technology, computer science, or engineering.
  - These include activities such as academic teams, clubs, camps, special interest groups, etc. Anything that wasn't a formal class that got you interested in technology.
- Did you ever use physical prototyping technologies in these activities?

- Prototyping technologies include paper prototyping, 3D printers, laser cutters, Arduino, electronics, etc.
- If you answered yes to the question above, what prototyping technologies did you use?

#### **Section 4 – College Selection**

- Please list any colleges you considered or applied to
- Please list any majors or programs you considered
- What motivated you to come to Berry College?
- What major(s) did you select when you first came to Berry College?
- Why did you select this major(s)?
- Did your high school experience affect your college/major selection? If so, how?

#### **Section 5 – Formal College Experience**

- What is your current major?
- What is your current minor (if any)?
- Have you changed majors while at Berry College?
  - If you answered yes to the question above, please list your previous major and reason for changing.
- If you are currently a Creative Technologies major or minor, what motivated you to join the program?
- If you are \*not\* currently a Creative Technologies major or minor, what has kept you from joining the program, or why did you leave the program?
- How did you hear about the Creative Technologies program?
- What interests you about the program?
- What concerns do you have about the program?

#### **Section 6 – Creative Technologies Classes**

- Which of these CRT classes have you taken?
  - CRT 101, CSC 103, CSC 235, PHY 240, CRT 300, CRT 310, CRT 320, MGT 340, CRT 499
- Have any of these classes been different than other courses you've taken in college? If so, how?
- Have any of these classes been similar to courses you've taken in high school? If so, how?
- Did any of these courses influence your decision to join or not join the Creative Technologies program? Why or why not?
- How have hands-on learning experiences affected your experience in these classes?
- How useful have the following activities been in your Creative Technologies courses?
  - Project-Based Work
  - Problem-Solving Exercises
  - Hands-On Learning Experiences
  - Group Work

- Rapid Prototyping/Design Exercises
- Lectures
- Homework Assignments
- Readings/Textbooks
- Project Pinups
- Project Presentations
- Prototyping Open House
- Student Research Symposium
- Critiques from Instructor
- Critiques from Classmates
- Critiques from Guests/Visitors
- Help from Mentor/Lab Assistants
- Open Lab Hours
- 24/7 Access to the Lab
- Digital Fabrication Tools (3D Printers, Laser Cutters, etc.)
- Design Surfaces (Movable whiteboards, hanging whiteboards, writeable surfaces on desks and lab tables)
- Project Posters
- Project Instructables
- Portfolios
- User Testing
- Of the activities listed in the question above, which have had the *\*biggest\** impact on your learning, and why?
- Of the activities listed in the question above, which have had the *\*least\** impact on your learning, and why?

### **Section 7 – Informal College Experience**

- What activities or organizations have influenced your interest in technology?
  - These could include friends, clubs, organizations, labs, talks, jobs, or experiences you've had while at college.
- How did you hear about HackBerry Lab?
- How often do you visit HackBerry Lab?
- Describe an experience when you received help from someone at HackBerry Lab.
- Describe an experience when you helped someone at HackBerry Lab.
- What are the strengths of HackBerry Lab?
- What are the weaknesses of HackBerry Lab?

### **Section 8 – Lab Usage**

- To what extent do you feel that HackBerry Lab achieved the following?
  - Provide students with free access to hands-on, state-of-the-art prototyping technologies
  - Serve as a cultural hub and meeting ground
  - Encourage design within curricula including introductory design courses, multidisciplinary design courses, capstone design courses
  - Encourage design in extracurricular activities, organizations, and teams

- Encourage collaboration between diverse teams of students from all years and majors
  - Welcome all types of projects, personal and professional
  - Excite students for careers involving creativity, design, innovation, and invention
  - Enable students to engage in open-ended, real world challenges
  - Serve as an exhibit and tour space to showcase student work
- Tell us about the time you spent doing the following activities
  - Hanging Out
  - Mentoring
  - Meeting
  - Creating
- What types of projects did you use the space for?
  - Class Projects
  - Personal Prototyping Projects
  - Personal Art Projects
  - Competition Projects
  - Research Projects
  - Entrepreneurial Projects
- How did spending time in the space impact the following?
  - Skill in design
  - Outlook on Engineering
  - Skill in Manufacturing
  - Safety
  - Employment Prospects
  - Teamwork
  - Friends
  - GPA

### **Section 9 – Post-Graduation Plans & Experience**

- Do you currently have a resume?
- Do you currently have a portfolio (electronic or printed)?
  - If you answered yes to the above question, how has your portfolio affected your job search or interviewing?
- Have you worked at (or will soon be working at) an internship?
  - If you answered yes to the question above, how has that internship shaped your experience in the program?
  - How did you find your internship?
  - What skills have you used the most at your internship?
  - Has the program prepared you for your internship? Why or why not?
- If you have not graduated, describe your ideal job or career field when you graduate.
- If you are currently working (not including student work), describe your job and how you found it?
- What skills have you used the most at your job?
- Has the program prepared you for your job? Why or why not?



- Are you considering attending graduate school (Masters or PhD program)? Why or why not?
  - If you answered yes to the question above, what schools/programs are you considering?
- If you are currently in (or have finished) graduate school, did the Creative Technologies program prepare you for it? Why or why not?
  - What skills have you used the most at grad school?

## **APPENDIX E. PROJECT TECHNOLOGY DIVERSITY STUDY**

### **DATA**

This appendix contains data gathered during the Project Technology Diversity Study. It looks at the types of technologies used by students in their intermediate and final projects during Berry College's CRT 101 Introduction to Prototyping course where the prototyping curriculum was implemented.

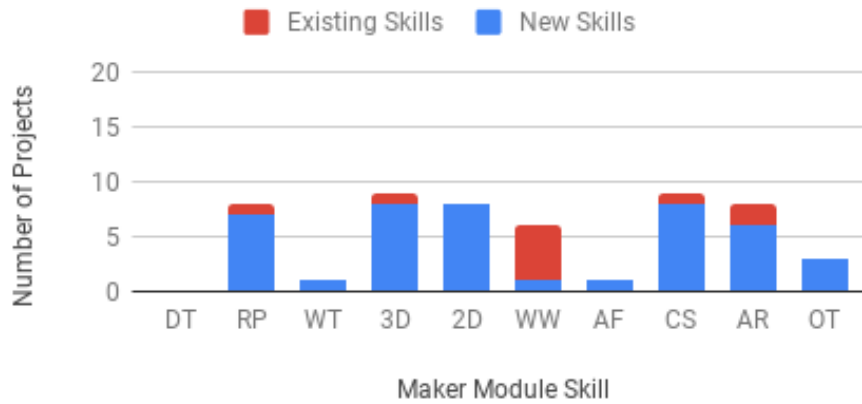
#### **Course Offering Summary**

<b>Course Code</b>	<b>Year</b>	<b>Semester</b>	<b>Total Students</b>	<b>Majors</b>	<b>Non-Majors</b>
ITP-F15	2015	Fall	17	6	11
ITP-S16	2016	Spring	19	7	12
ITP-F16	2016	Fall	23	10	13
ITP-S17	2017	Spring	23	8	15
ITP-F17	2017	Fall	20	11	9
ITP-S18	2018	Spring	25	17	8

## Technology Diversity Data

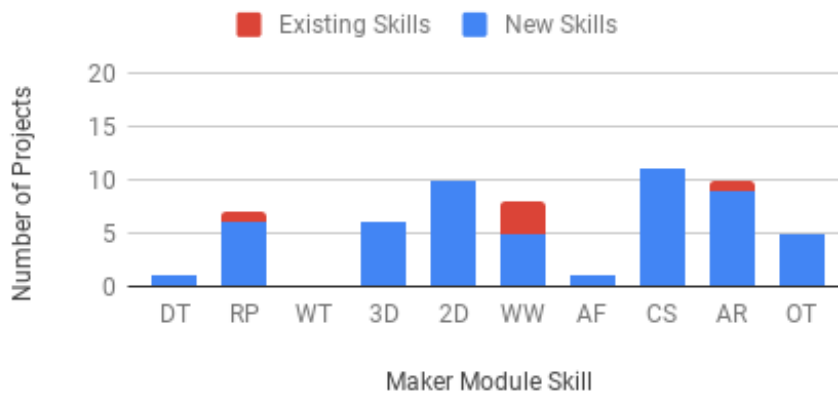
### ITP-F15 Intermediate Project Technology Usage

n = 17 projects



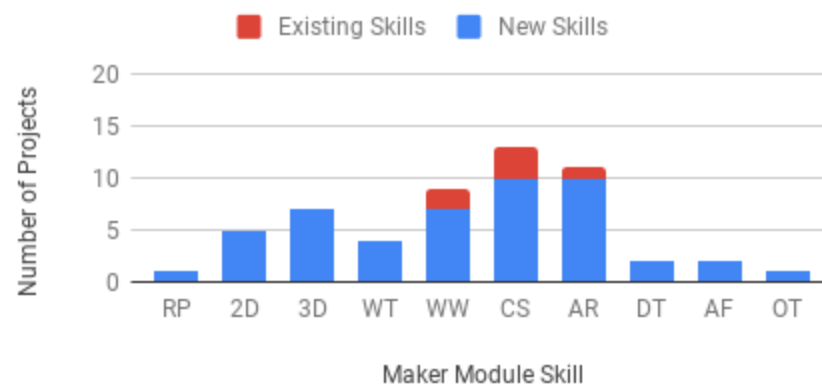
### ITP-F15 Final Project Technology Usage

n = 17 projects



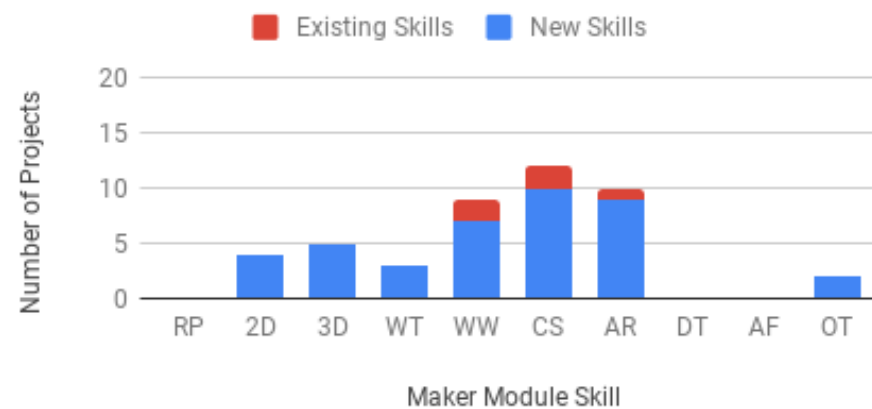
## ITP-S16 Intermediate Project Technology Usage

n = 19 projects



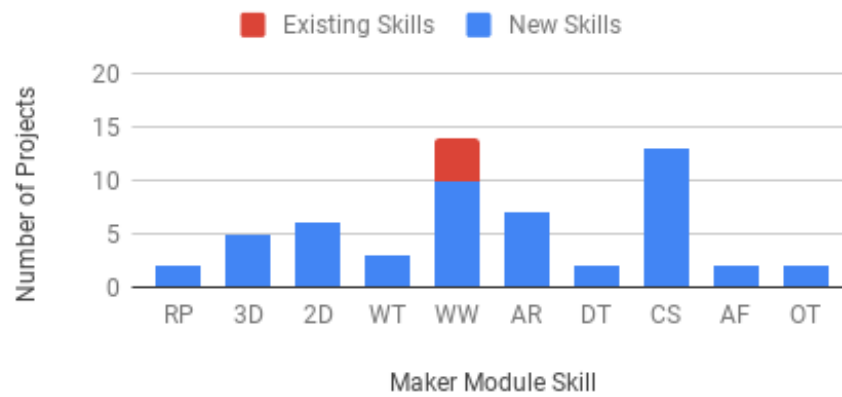
## ITP-S16 Final Project Technology Usage

n = 19 projects



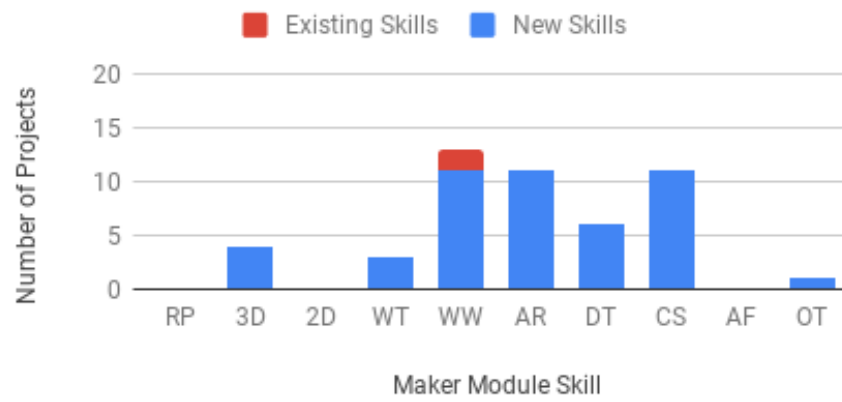
## ITP-F16 Intermediate Project Technology Usage

n = 23 projects



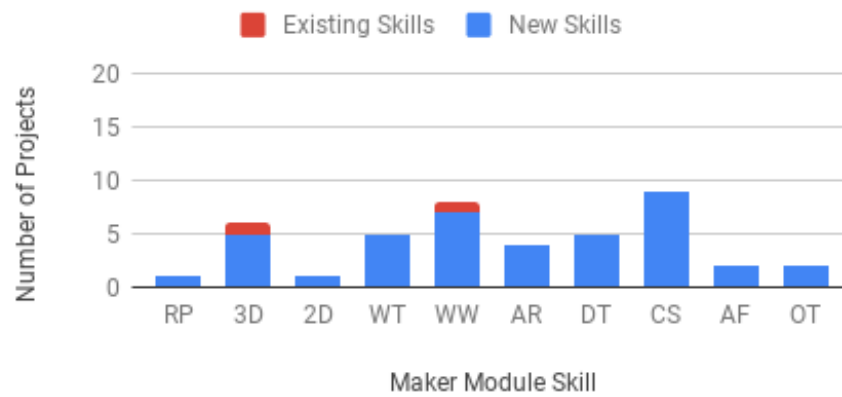
## ITP-F16 Final Project Technology Usage

n = 23 projects



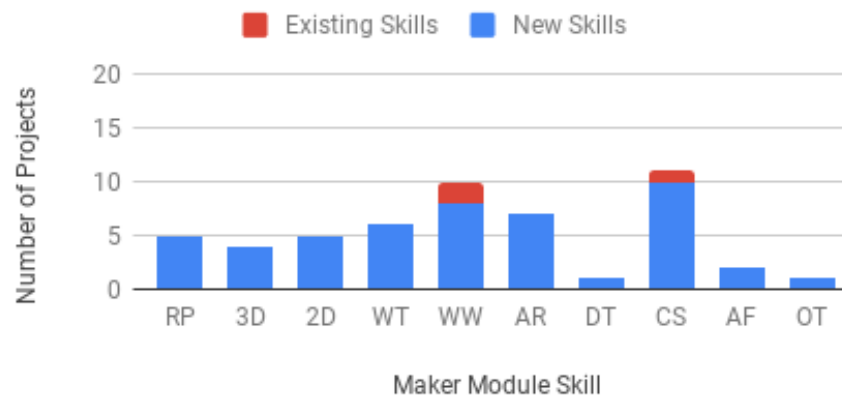
## ITP-S17 Intermediate Project Technology Usage

n = 22 projects



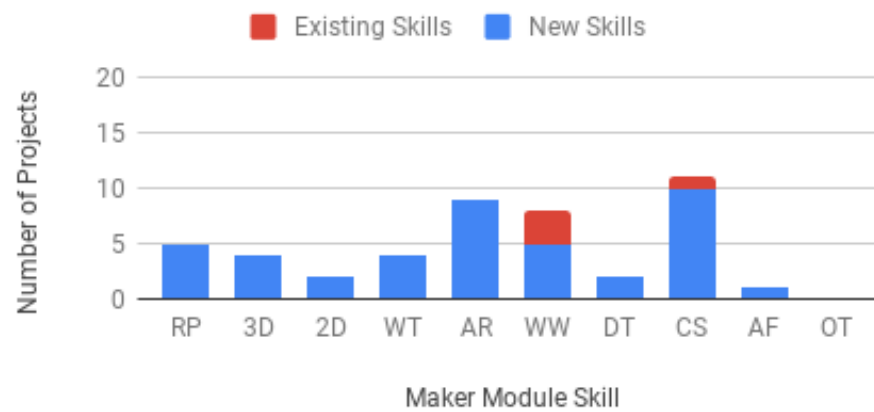
## ITP-S17 Final Project Technology Usage

n = 22 projects



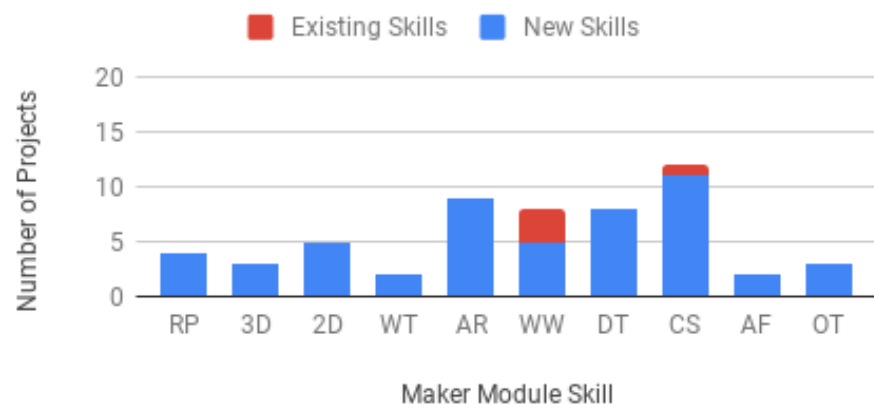
## ITP-F17 Intermediate Project Technology Usage

n = 20 projects



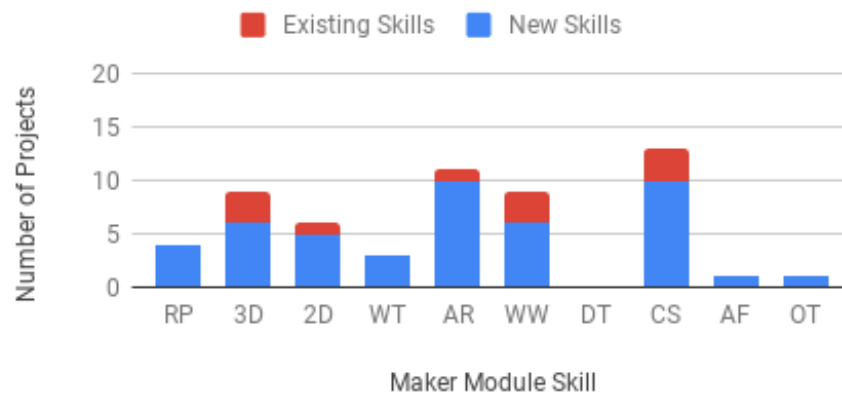
## ITP-F17 Final Project Technology Usage

n = 20 projects



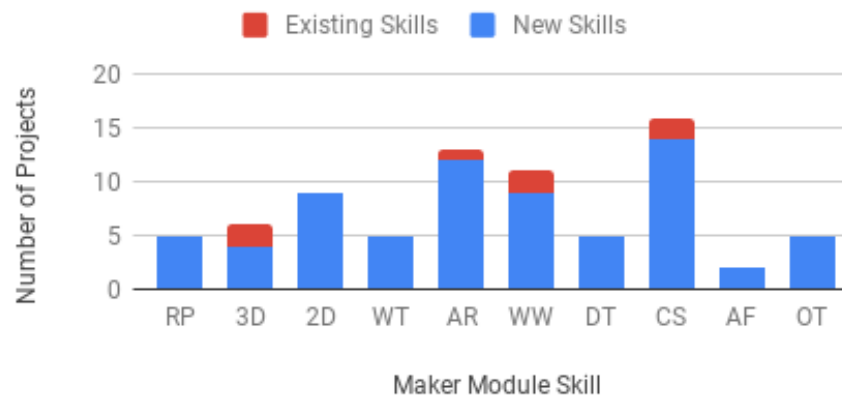
## ITP-S18 Intermediate Project Technology Usage

n = 25 projects



## ITP-S18 Final Project Technology Usage

n = 25 projects





## **APPENDIX F. SAMPLE MAKER MODULE CURRICULUM: RAPID FOAM BOARD PROTOTYPING**

In this curriculum chapter, students are introduced to the basic concepts of rapid prototyping as a means for quickly producing tangible concepts that can be examined and evaluated. Students will become familiar with a model of interactivity that helps them understand basic principles of human-centered design, as well as develop skills in manipulating foam board to create simple paper prototypes. They will explore these concepts through the creation of an interactive lamp concept.

### ***Introduction***

Innovation is happening all around us at an immense pace. To keep up with the progress of technology, it is necessary to learn how to bring ideas into the real world quickly and efficiently so that they can be evaluated, tested, and iterated upon. This process of quickly bringing ideas into the real world is called rapid prototyping. This can be thought of as a type of brainstorming where ideas take on a physical form instead of just ideas on paper. It should be noted that this process is not a replacement for traditional brainstorming techniques (which we will also employ), but rather a way to explore real world constraints as part of the design process. We have all had an experience where we could picture something perfectly in our minds and have the real thing turn out quite differently. Rapid prototyping helps designers, engineers, and technologists understand potential issues early on in the design process so that they can be addressed in the first few stages of planning.

Thankfully, there are a variety of techniques and technologies to assist in that process. Digital fabrication tools such as 3D printers, laser cutters, CAD software, programmable microcontrollers, and even paper and cardboard, are critical tools in helping make important design decisions early on. In this chapter, we will explore the concept of rapid paper prototyping as one of these tools used to explore real world constraints in context of a creative design challenge.

Any rapid prototyping technique must meet a few significant criteria in order to be considered valid. These criteria include being fast, inexpensive, and “good enough.”

Criteria 1: Fast. As its name implies, rapid prototyping must be fast. This fastness can be interpreted in two ways. The first is that the methods, tools, and materials should produce results in a reasonably quick amount of time. In traditional brainstorming sessions it is not uncommon for participants to use sticky notes, sketch pads, and dry erase boards because these tools enable them to quickly write and draw their ideas. Similarly, in physical prototyping, we must use tools and technologies that allow us to quickly shape and form our ideas in the real world. It would be silly to force participants in a rapid brainstorming session to carve their ideas on stone tablets, and it is similarly insensible to rapidly prototype with tools that take an unreasonable amount of time to produce results. By utilizing technologies that can quickly produce prototypes, not only is it possible to explore a wide variety of possible design solutions, it is reasonable to iterate and improve on those ideas without an enormous investment of time.

The second way in which we can understand fast is to mean that rapid prototyping should operate under constrained and oftentimes demanding time limits. Operating under self-imposed time limits is not only a valuable simulation of the real-world deadlines that

designers face, but also introduce a constructive constraint that will help participants think quickly and creatively. When facing a ticking stopwatch, it is easier to lower one's inhibitions about what is a "good idea" and will instead consider a variety of ideas, especially those beyond the norm. It is these ideas that push on the edges of typical norms where innovation and creativity can often be found. It is important, however, to understand that like most skills, thinking under pressure is a skill that is developed with practice. In time, it will become easier and easier to think broadly and deeply during these rapid sessions.

Criteria 2: Cheap. Using inexpensive materials is not just a familiar limitation for college students living day to day on a steady diet of ramen noodles. Using cheap and simple materials brings a variety of additional benefits to the world of rapid prototyping while. In the technology industry, prototyping is an incredibly costly process. As designs progress toward mass production, each change and iteration represents enormous costs in both resources and time. Furthermore, costs rise exponentially the closer those revisions are to mass production and so there is an incentive to discover flaws in designs early on in the design process. Cheap materials also enjoy the benefit of often times being readily available. These materials benefit from an economies of scale effect that drives their price down and are available across a number of retailers, both local brick-and-mortar shops and online retailers alike. This is particularly important because it gives the designer a variety of options to be flexible with suppliers. For example, many of the supplies and materials used throughout this text are sourced from retailers like Walmart and Amazon, each of which provides distinct advantages to the rapid prototyper. For late nights, it is

convenient to be able to access materials at a 24-hour Walmart, or have items delivered in one or two days from Amazon at competitive prices.

The other advantage of using cheap materials is that it helps designers avoid the sunk cost fallacy. The sunk cost fallacy explains the natural reluctance to abandon ideas that are known to be bad because of the amount of resources that have already been invested in them. By using inexpensive materials and tools, it is easier to stave off this point of no return scenario because there are relatively little material resources invested earlier on. It is much easier to accept criticism when those changes are still relatively easy to implement and the costs of that implementation are low. By using inexpensive materials, designers can literally toss bad ideas in the trash without feeling guilty about wasting precious resources. In doing so, they will be able to improve on their ideas and concepts and when it comes time to fabricate with better materials, many design flaws will have already been addressed.

Criteria 3: “Good Enough”. The primary goal of rapid prototyping is to test the validity of an idea. It helps designers explore significant questions of physical constraints, human factors, aesthetic appeal, and core functionality. It is not intended to produce high-quality products that are ready to be shipped off to be stocked on store shelves. Too often, in the excitement of forging ahead with an exciting new idea, it is easy to get bogged down in small details that draw attention away from larger, fundamental issues. Thus, rapid prototyping methods should focus on creating artifacts that are “good enough” to clearly convey the idea and provide just enough detail to allow the designer to solicit feedback on well-defined design goals. For example, consider this image:



*This papercraft gorilla represents a low-fidelity approach to rapid prototyping.*

Among the simple shapes and shades, do you see a gorilla? Despite its relatively simple appearance and inexpensive prototyping method (in this case papercraft), the designer has managed to convey a precise thought in your mind. With this, you could easily begin to ask a variety of questions that would stimulate thoughts about next steps. For example, with this figure, there may be a consideration regarding scale. Is this the right size for the required application? Had we been looking at a photo of a gorilla on a

computer screen, it may be more difficult to make such assessments than having an inexpensive physical prototype in front of you.

The philosophy of “good enough” not only has a strong foundation of helping designers get feedback to a specific set of design goals, but also to help them dissuade feedback on design features that are not yet important. For example, despite the ability of modeling 3D CAD and rendering programs to create photorealistic renderings of buildings, it is still the practice among many architectural firms to present concept work to clients in the forms of sketches and water colorings. Why would these firms show clients basic floor plans instead of allowing them to tour a potential space in 3D virtual reality? The answer is during these early stages, the designers are trying to address questions of a building’s overall footprint, meaning, and purpose. These “good enough” representations of the building allow clients to focus on these questions rather than a particular patterning in the brickwork or carpet texture.



*An architectural watercolor allows designers and clients to focus on important design goals such as usage and footprint, while avoiding unnecessary details during early prototyping.*

For the perfectionist, the concept of “good enough” can be a frustrating one. Like many things in life, this concept presents a Goldilocks dilemma, i.e. not too simple, not too complex, but just right. Fortunately, when paired with the time constraints detailed in criteria 1, there is a finite amount of time in which to spend on unnecessary details.

### ***Skills Building and Warm Up Activity***

To help fortify these rapid prototyping concepts, we will explore a very common approach to creating physical prototypes - rapid paper prototyping. In this exercise, we will explore tools and techniques necessary to creating paper prototypes that will be required for the design challenge later in this chapter.

*Warm Up Activity - Foam Board Basics.* The goal of this activity is to develop and refine the skills necessary to create basic shapes using foam core. By learning how to cut and join this material, it will be possible to develop low-fidelity paper prototypes.

Foam board or foam core is a robust paper prototyping material that has a variety of properties that make it excellent for creating rapid prototypes. It is a laminate material, meaning that it has a top and bottom layer of thin paper, and a center layer of foam. Sheets are usually 20 x 30 x 0.2” and cost around \$1 per sheet and can be found at hobby stores, office supply stores, Walmart, and online. Larger sheets in a variety of thicknesses are also available. The unique construction of foam board allows it to take on many

shapes and can be manipulated to both flexible and sturdy. Though light and easy to cut, it is sturdy enough to create structures that can bear the weight of a person on it.

In terms of classroom preparation, there should be ample workspace on tables as well as easy access to electrical outlets. Because students will be working with X-Acto knives and hot glue guns, it is advisable to have a first aid kit nearby in case of cuts or burns.

Organize into groups of two or three (for larger classes, groups as large as five are acceptable). Each group will need a full sheet of foam board, X-Acto knives, hot glue guns, hot glue sticks, and cutting mats (for cutting mats we cut down a 48 x 96" piece of hardboard into 24 x 24" mats from the hardware store).

Cut the foam board into equal sized pieces for each member of the group. While holding the X-Acto knife like a pencil, practice cutting 2-inch strips of foam board as straight as possible. You will find it helps to keep the angle of the blade low to allow it to make as much contact with the foam board as possible. If your knife is sharp, you will only need medium pressure to cut all the way through. Be careful to keep fingers out of the way of the blade - it is razor sharp!

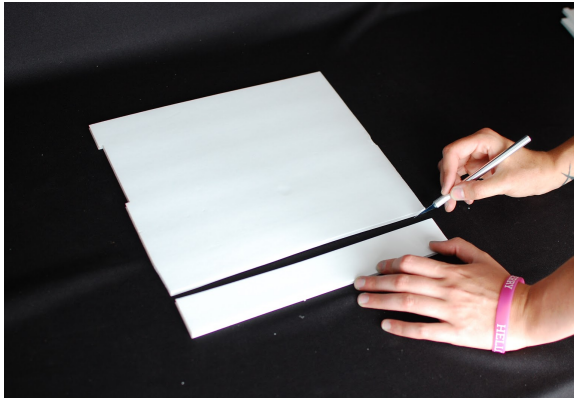




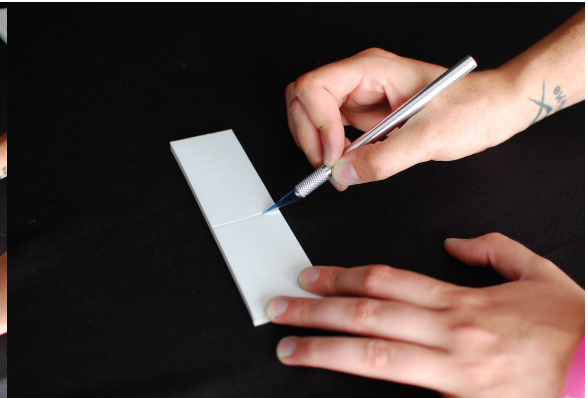
*For best results, hold the X-Acto knife like a pencil and cut using a low, shallow angle.*

Gather several of your 2-inch strips of foam board (at least 6 inches in length). These strips will be used for practicing the four basic joints in foam board prototyping. These joints allow you to create a variety of geometries when building models. While there are a number of ways to cut and combine foam board, these basics will get you started in the right direction. Take a few minutes to build each of the four following joints.

Sharp Joint - The sharp joint has a distinct 90-degree angle and relatively sharp corner. It is the most common joint and is very versatile for creating enclosures, boxes, etc. Follow the instructions below to create a sharp joint.



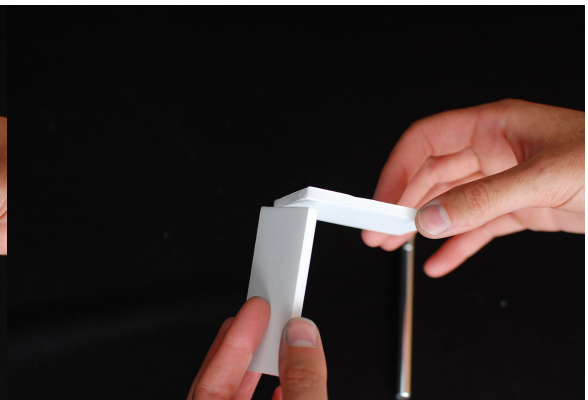
**Step 1** - Cut a strip of foam board approximately 2 inches wide and 6 inches long. All cuts should be done on a cutting mat or board.



**Step 2** - Apply light pressure and make a shallow cut across the width of the foam board strip. This cut should go through the top layer of paper, the middle layer of foam, but *\*not\** the bottom layer of paper.



**Step 3** - Open the joint outward by gently bending each side of the cut. Remember, the bottom layer of paper should be intact. If you accidentally cut this layer, try again with a new foam core strip.

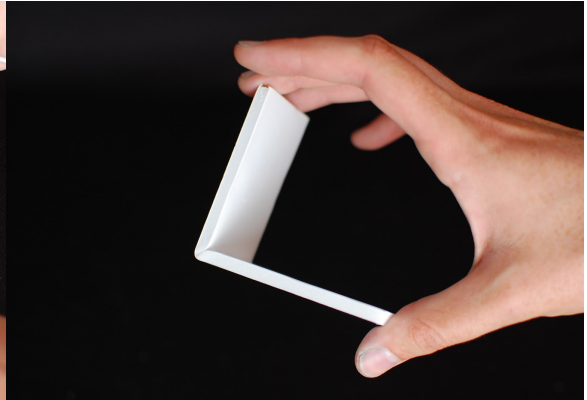
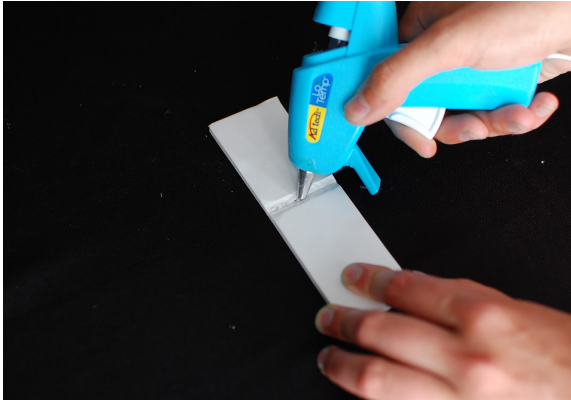


**Note** - If you press down too hard during step 2, you will cut through the bottom layer of paper and your joint will separate. If this happens, cut a new strip of foam board and try again.



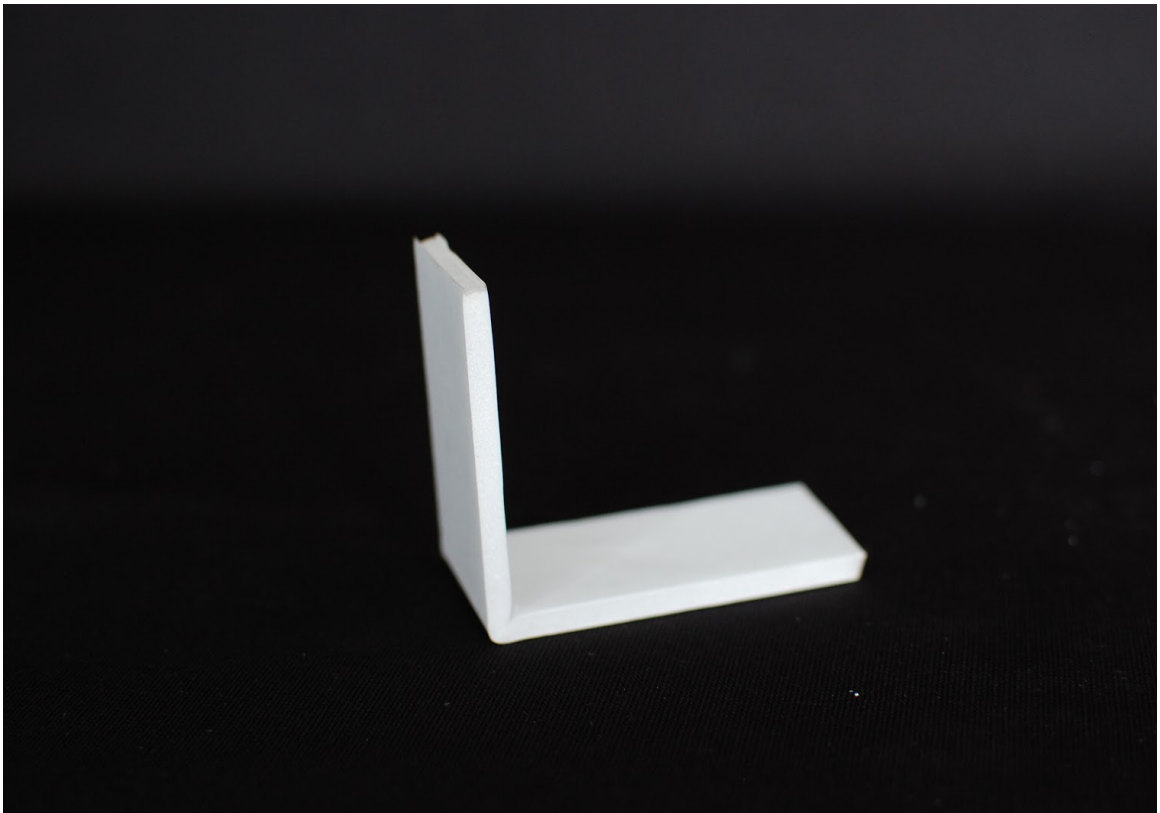
**Step 4** - Lay the strip down with the cut side facing up. Use the blunt end of the X-Acto handle to compress the foam down around the cut. Be careful not to cut yourself with the exposed blade of the knife.

**Note:** Here is a close-up view of compressed foam. Note the V-shaped indentation made by the handle of the knife.



**Step 5** - Apply a bead of hot glue to the section of compressed foam.

**Step 6** - Bend the foam inward to the desired angle and hold for about 30 seconds until the hot glue has cooled and the angle holds its shape.



**Completed** - Once the hot glue has cooled, you will have a sharp foam board joint!

*Process steps for creating a sharp joint from foam board.*

Slight Radius Joint - The slight radius joint is very similar to the sharp joint with the exception that it has rounded corner. The rounded corner is a favorite among designers and engineers alike, and it is useful for creating both acute and obtuse angles. Follow the instructions below to create a slight radius joint.



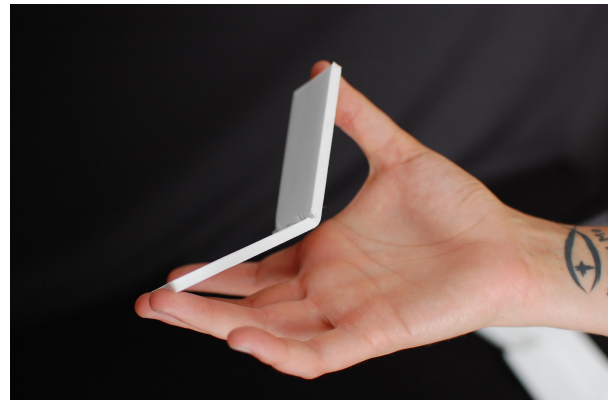
**Step 1** - Cut another strip of foam board and begin this joint by dragging the blunt handle of the X-Acto knife across the width of the foam.



**Note** - You should notice a deep indentation in the board where you compressed the foam.

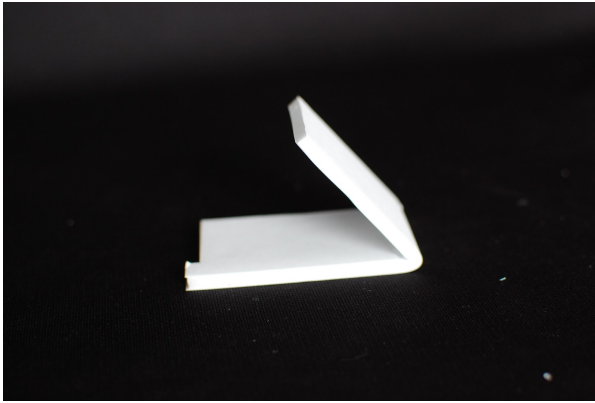


**Step 2** - Apply a bead of hot glue to the section of compressed foam.

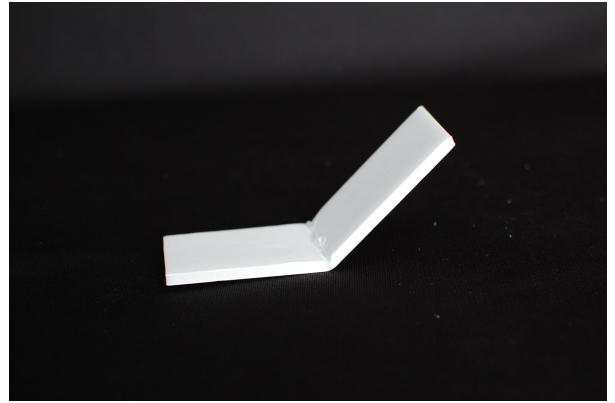




**Step 3** - Bend the foam inward to the desired angle and hold for 30 seconds until the hot glue has cooled and the angle holds its shape.



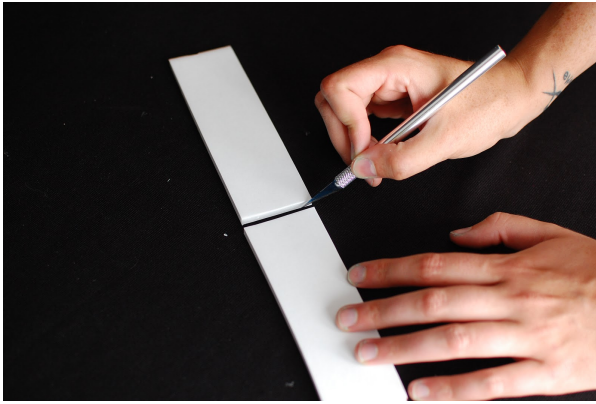
**Completed** - Here is a sample of an acute angle made using this method.



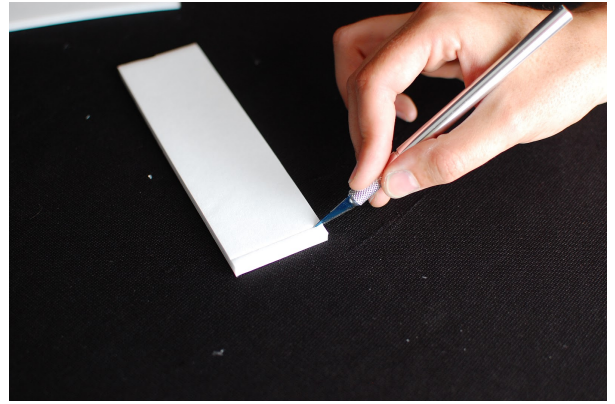
**Alternative** - Here is a sample of an obtuse angle made using this method.

*Process steps for creating a slight radius joint from foam board.*

Lap Joint - The previous two joints are very useful when needing to make a bend in a single piece of foam board. However, when joining two separate pieces of foam board together, a lap joint is an excellent choice. By overlapping the edges of the joined pieces, two points of contact are made and create a strong joint. Follow the instructions below to create a lap joint.



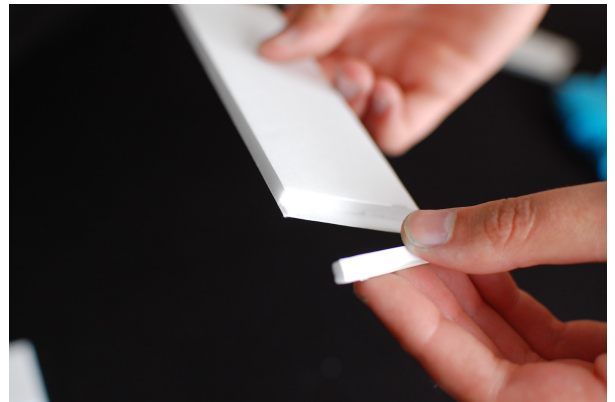
*Step 1 - Cut the foam core strip into two equal sections.*



*Step 2 - Apply light pressure and make a shallow cut across the width of the foam board strip. This cut should be about 1/4" from the edge of one piece. It should go through the top layer of paper, the middle layer of foam, but *\*not\** the bottom layer of paper.*



*Step 3 - Make an incision into the foam along the edge of the cut near the bottom paper layer.*



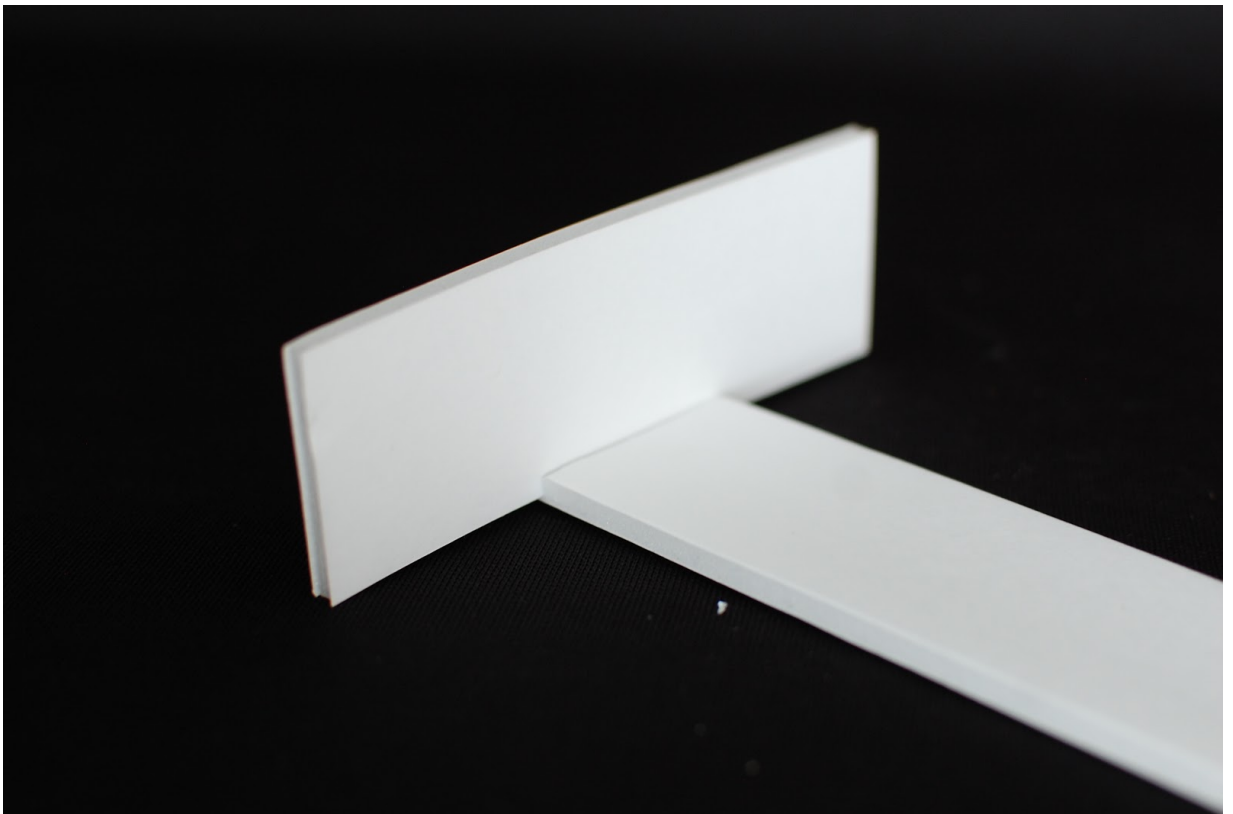
*Step 4 - Gently peel away the section of foam made by the cuts in steps 2 and 3.*



*Step 5 - Apply a bead of hot glue to the bottom layer of paper and the exposed foam edge of the lap joint.*



*Step 6 - Attach the second piece of foam board and hold for about 30 seconds until the hot glue has cooled and the angle holds its shape.*



*Completed - Once the hot glue has cooled, you will have a completed lap joint.*

*Process steps for creating a lap joint from foam board.*

Large Radius Joint - With the previous three joints it would be difficult to create more complex geometries in a foam board prototype. However, the large radius joint allows for an enormous amount of variation and organic curves. It is the most difficult of the four basic joints, but can yield tremendous results.



*Step 1 - Apply light pressure and make a series of shallow cuts across the width of the foam board strip. Each cut should roughly be the same distance from the others. The cuts should go through the top layer of paper, the middle layer of foam, but *\*not\** the bottom layer of paper.*

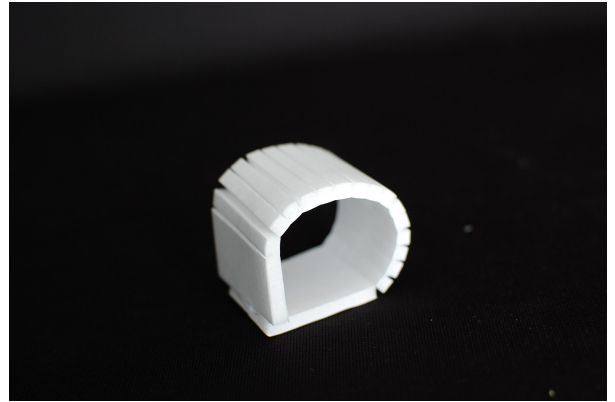


*Step 2 - Bend and flex the foam core backward to loosen each of the cuts. Now you can shape the curve of the foam core to you needs.*

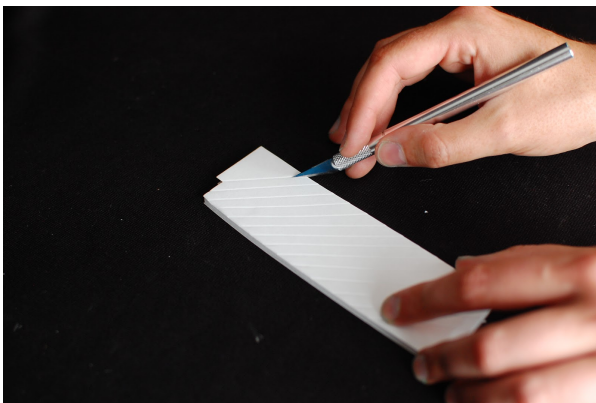




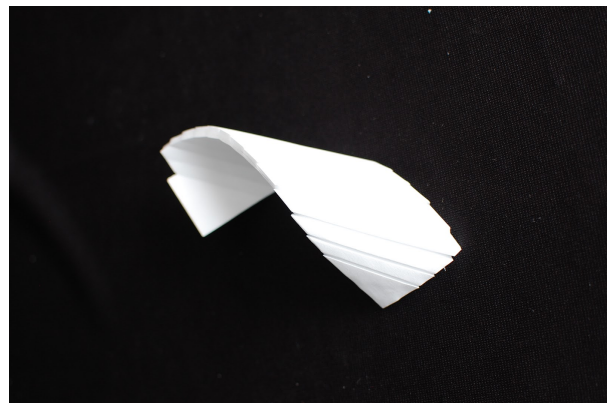
*Step 3 - Bend to the desired final shape and attach with hot glue.*



*Completed - When the hot glue has cooled, you will have a large radius joint.*



*Alternative - Using the same technique above, make a series of cuts into the strip but cut them at an angle instead.*



*Alternative Completed - Bend and flex the foam and you will have a helical spiral that you can use in your design.*

*Process steps for creating a lap joint from foam board.*

With these basic joints mastered, you are now able to put these skills to work with a creative design challenge!

### **Problem-Based Design Challenge**

In this design challenge, you will take on the role of an interaction designer tasked with the goal of creating an interactive lamp concept using foam board.

### Expectation

In this design challenge we will explore the concept of interactive lamps and define a *model of interactivity*. You will then work through a creative design process and use foam board prototyping to create a novel, interactive lamp concept.

### Exposition

Some of the simplest devices we interact with on a daily basis are lights. Whether they are overhead fluorescent lights, traffic signals, out-of-order lights on a soda machine, or even a night light, lamps provide a variety of useful functions and are a great context in which to practice rapidly prototyping. In this design challenge, you will be thinking about what would make a novel, interactive lamp. But first, we need to define a few terms.

First, what is a *lamp*? When we hear that word, most of us probably imagine a lamp similar to the one pictured here.

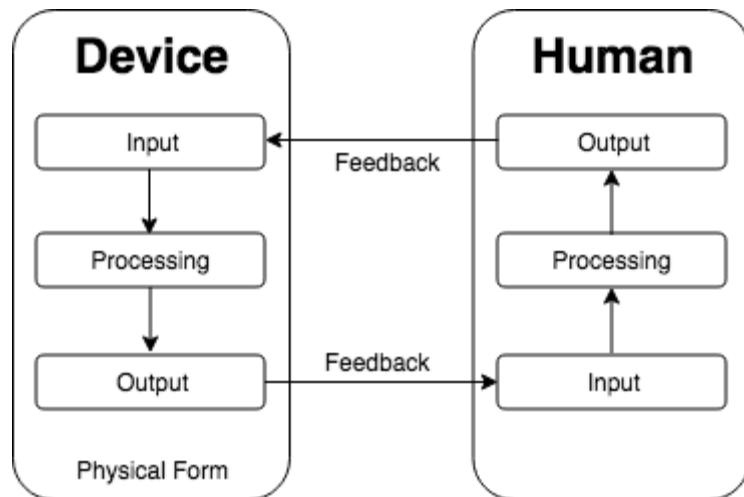


*A common, household desk lamp.*

This is a fairly standard desk lamp that you may have sitting on your workspace. However, for this exercise, we will be thinking about lamps in a much broader sense. In fact, we'll consider any sort of electronic light source that responds to some sort of stimulus to be a lamp.

A lamp's ability to respond to some sort of action brings us to our next term we must define - *interactive*. In the case of the desk lamp pictured, would you describe it as interactive? One way of defining interactive is to say that one thing influences another. For example, the light bulb will turn off and on in response to the user flipping the rocker

switch off and on. That is to say, that the light bulb (output) is *reactive* to the rocker switch (input). But would you say this is highly interactive? Most would say not. A more interesting example of an interactive lamp would be one that incorporates feedback into the device. That is to say that the user responds in a more contextually rich manner than simply observing that the light has turned on. For example, consider a four-way intersection of roads. In this case there is a high level of interactivity as lights interact with drivers and pedestrians. From sensors embedded within the roads to crosswalk signals, a casual observer can quickly see the delicate balance of interaction between travelers and these lights. The complexity of how both device and user respond to each other creates a *model of interactivity* that we will refer to often.



*This model demonstrates the relationship between devices and humans.*

In this model, you can see the constant cycle of interaction between humans and devices. These interactions rely on a feedback loop whereby information is exchanged through inputs and outputs. The input received in each system is then processed. In

devices this occurs through circuitry or programming to determine an appropriate reaction that is communicated through an output. In this model, we differentiate from other similar systems by indicating that the device has a physical form and take into consideration the role that form plays in embodying the input, processing, and output components of the device, as well as how it affects a user's ability to interact with the device.

With this refined definition of interactivity in mind, let's visit another concept and see how it compares to that ordinary desk lamp. This is Pinokio, an interactive lamp concept developed by Shanshan Zhou, Adam Ben-Dror, and Joss Doggett at Victoria University of Wellington:

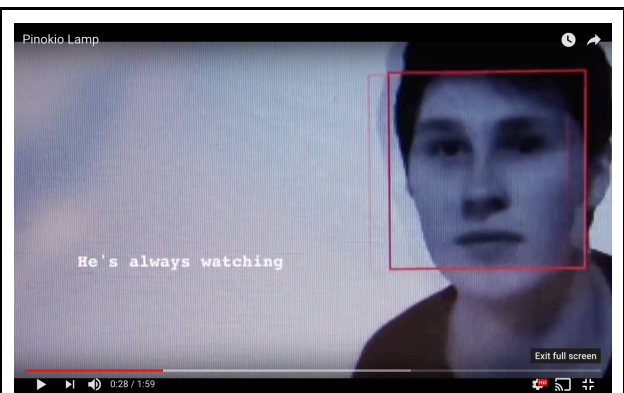


*This unassuming lamp is concealing a variety of functions and behaviors.*

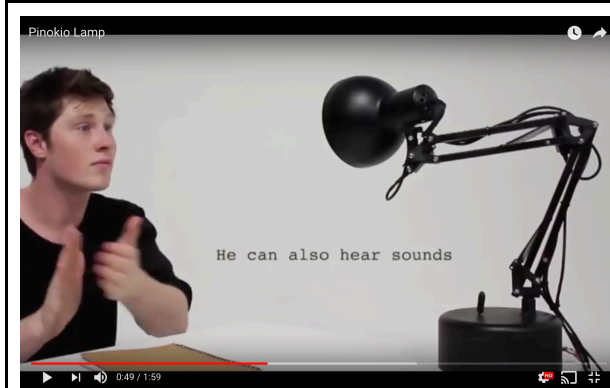
Upon first glance, it does not appear to be all that different from the original lamp. However, concealed within this lamp are a variety of systems that allow it to creatively interact with its user.



The lamp contains servo motors, a webcam, Arduino microcontroller, and uses the Processing programming language to control its behaviors.



Facial recognition software responds to the user's face so that the lamp is always "looking" at the user.



If the lamp becomes distracted or bored, the user can call it to attention by clapping.



The external on/off switch *should* turn the lamp off, but when switched, the lamp uses its head to turn itself back on.

*Interactive functionality of the Pinokio Lamp.*

The designers of this lamp have created a unique experience by carefully thinking through what meaningful feedback means between the user and device. It is these unique and novel experiences that you will think about and design in this activity.

Finally, let us consider the role that physical form plays in supporting interactivity. The aesthetic and shape of a device has a powerful influence over our relationship with a device. The satisfying click of a switch, the smooth curves of a cell phone in our hands, or the textured bumps on the home keys on a computer keyboard, all affect our ability to properly use our devices. Let us consider one last interactive lamp as an example.

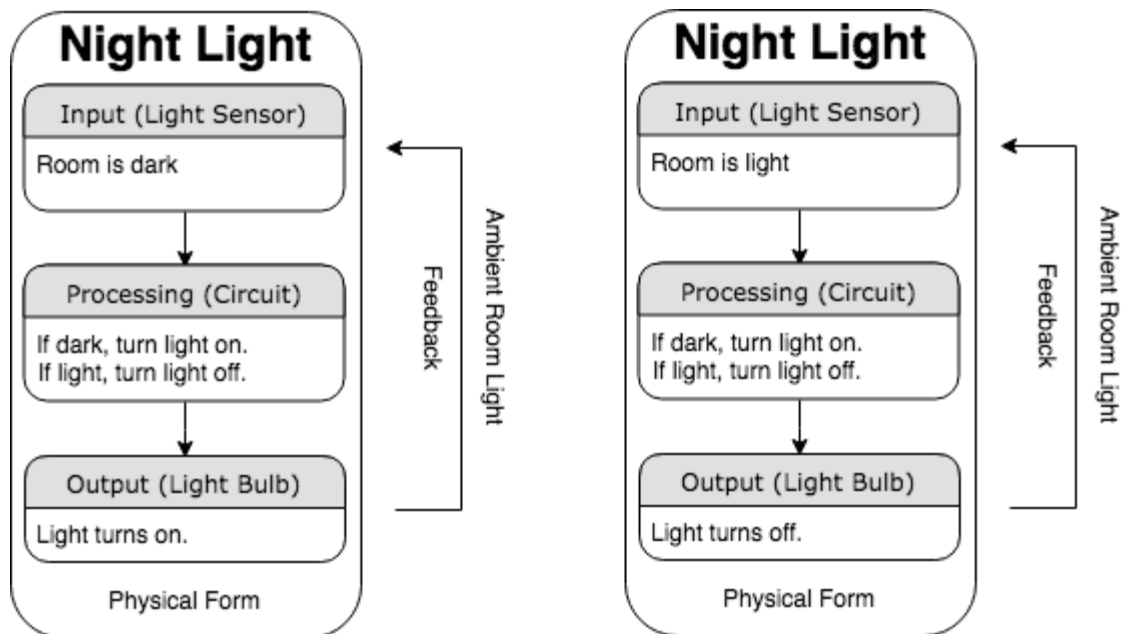


*A standard home night light for a child's room.*

The operation of this night light should be familiar to most. It operates on a relatively simple model of interactivity as it responds to its environment. Simply, when it is dark in the room, the night light turns on, and when it is light in the room, the night light turns off. However, it is easy to be deceived by this relatively simple function if we overlook the very clever physical form that makes its operation possible.



The role that the physical form plays in the function of this night light is straightforward to derive if we graph the devices model of interactivity.



*A model of interactivity for a night light shows two possible outcomes.*

In this model of interactivity, we see how the output of the night light could directly affect the conditions of the feedback by changing amount of ambient light in the room. If the sensor on the night light detects that it's dark, it turns on its light bulb. However, if this lights up the room, the feedback conditions change and the sensor would detect that the room is light. At this point it would turn off the light bulb and the cycle would start again resulting in an infinite feedback loop.

However, this feedback loop doesn't occur because of how the physical form of the light was designed. The aspect of the form is how the light from the night light is dispersed when it is on. In many cases, night lights will use a translucent lens to disperse

the light up and away from the light sensor in the device. This dispersion drops the amount of ambient light created by the night light to below the threshold embedded into the processing circuitry. Another aspect of the physical form of the night light that assists in eliminating a feedback loop is how the sensor is positioned within its enclosure. In most cases, it is set back such that it is not in the direct pathway of its own light. Without these physical form considerations, the operation of this device would be completely unreliable.

### Exploration

Organize into groups of two or three (for larger classes, groups as large as five are acceptable). Each group will need a full sheet of foam board (20 x 30”), X-Acto knives, hot glue guns, hot glue sticks, cutting mats, dry erase markers and board, LEDs, coin cell batteries, and tape.

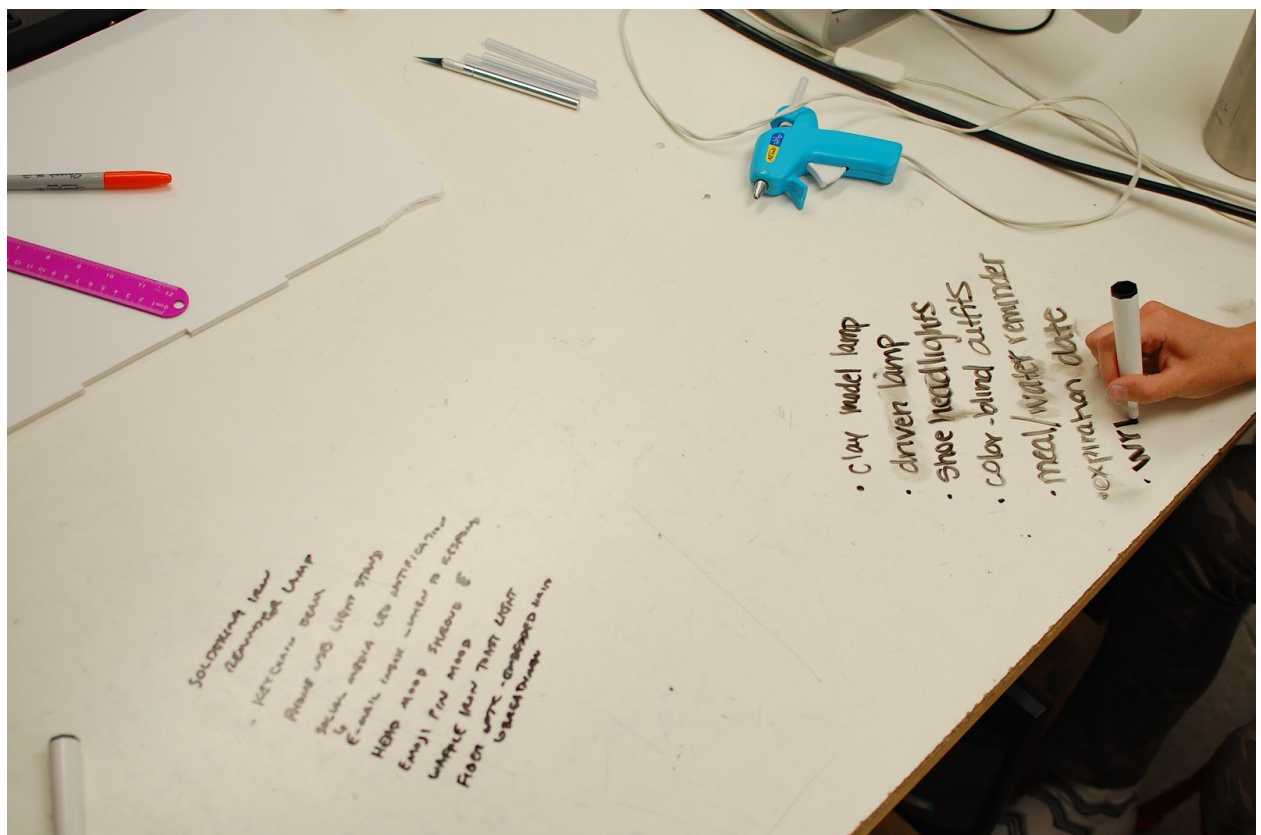


*Gather enough materials for each member of the group to participate in foam board prototyping.*

*Brainstorming (10 minutes)* - Set a timer for 10 minutes and begin talking with your group members about potential ideas for interactive lamps. During this session, any idea, no matter how absurd is valid. If a group member suggests a lamp that hovers above a user's head that turns on anytime the user has a good idea, jot it down and keep talking.

The goal of this session is to move away from bland ideas and think divergently. One approach to this will be thinking of personal problems you have encountered. Were you late for your first day of class because you couldn't find the classroom? Did you injure yourself during volleyball practice? Have you fallen asleep while reading a textbook? All of these personal issues are great starting points for thinking about an interactive lamp concept.

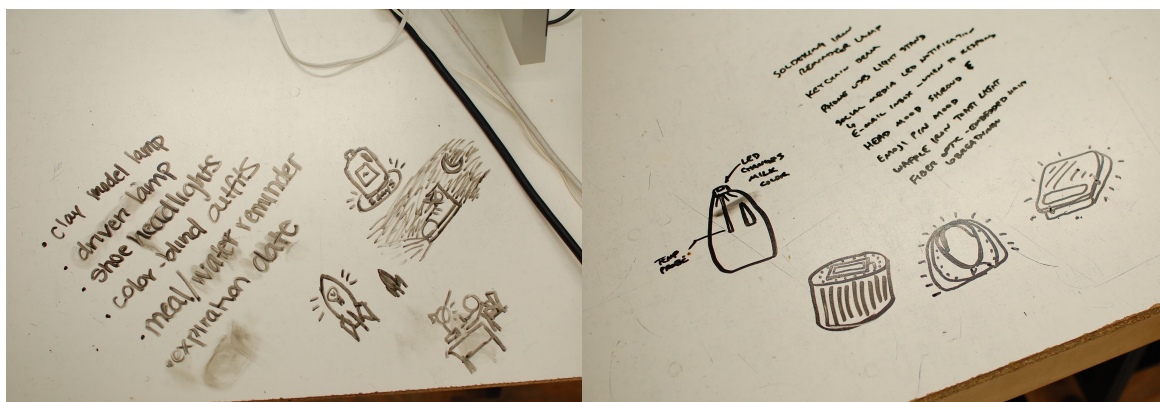
Keep in mind that for this activity you are allowed to think about the word “lamp” *very liberally*. If it lights up in some way, it’s a lamp. The important thing is to think about interesting concepts and focus on a meaningful model of interactivity. Also, it is important to remember that this is *paper prototyping*. This prototype will largely be non-functional but will serve as an important way to convey your idea and think through potential issues and opportunities for development. Spend the last few minutes narrowing down the most interesting concepts if your group has come up with several. When the timer goes off, stop and move onto the next section.



*Quickly write down ideas as they are discussed in your group. You can use pen and paper or the dry erase markers and boards.*

*Sketching (5 minutes)* - Sketching plays an important role as you prepare to transition from the abstract concepts you developed in the brainstorming section to the paper prototypes in the next section. Sketching forms that the interactive lamp could take will not only help you think about how to cut and measure your foam board, but it will help you think through how the user will interact with the device. Will it attach to their wrist, hover over their head, or sit on their desk? Sketching will help shape some of these parameters and use cases.

It is also important to remember the concept of “good enough” when it comes to the artistic quality of these sketches. They need to be just good enough to have a direction when it comes time to start prototyping. With this in mind, set a timer to five minutes, gather dry erase markers and boards, and create at least three sketches. In this case, it could be sketches of three different approaches to one of the ideas that your group discussed, or three sketches of three ideas your group discussed. At the end of five minutes, each group member should be ready to share their sketches.



*Sketches should be detailed enough to give a rough idea of the shape and features of the proposed design.*

*Paper Prototyping (30 minutes)* - As a group, spend the first five minutes sharing sketch concepts and quickly decide on a single concept. In some cases, this can be a compromise of ideas and sketches, but the important point is to decide quickly and start prototyping.

Once a design has been decided upon, quickly divide up tasks among the group members. Some group members can work on measuring and cutting, while others form joints and assemble. Another approach may be to have individual group members work on subassemblies and put the parts together at the end. It is important to work quickly and efficiently and keep an eye of the timer. This time limit will force you to focus on getting just enough together to convey the concept. As the prototype comes together, it is acceptable to draw on the model and add LEDs to help explain how the device would work.



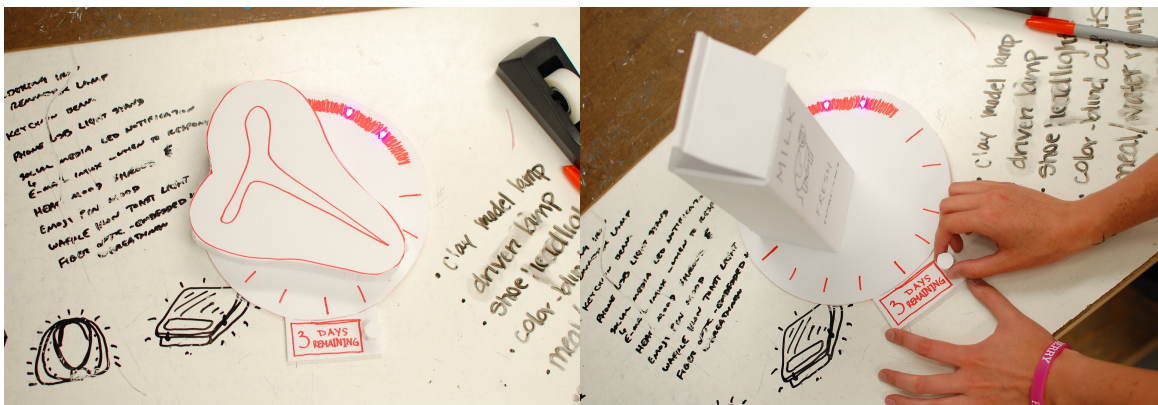
*Work quickly and divide up tasks among group members to create the foam board model of the idea. You can make the prototype light up by sliding an LED over a coin cell battery and taping it in place.*

*Explanation*



At the conclusion of the paper prototyping session, prepare to present your work and focus on the following characteristics of your prototype:

- *Describe the primary function or proposed use for your interactive lamp concept.*
- *Describe in detail the input, processing, and output of the lamp.*
- *Explain how users would interpret feedback from the lamp and how they would respond.*
- *Discuss how the physical form of the interactive lamp supports the proposed function.*



*This interactive lamp prototype uses a light up pad that sits in the user's refrigerator and allows them to monitor the expiration date of perishable items such as meat or milk. The embedded LEDs indicate how much time is left to use the item and changes color and intensity as the expiration date nears, allowing the user to make decisions regarding meal planning.*

### Expansion

After successfully completing the foam board prototype, take a few minutes to reflect on the exercise. What insights about your proposed design did you gain through physically building a model out of foam board? How well did your foam board prototype represent your initial concepts and sketches? Were you pleased with the outcome? If not,

what would you change about your model if you were given more time? What would the next steps be if you were to continue developing your concept?

Find an example of another interact lamp that you encounter throughout your day. Model its behavior using the model of interactivity. Evaluate how its physical form influences its function and discuss any potential improvements that could be made to the device.



## APPENDIX G. POWER REQUIREMENTS WORKSHEET

<b>Maker Module</b>	<i>Module Name:</i>							<b>Classroom Information</b>	
<b>Equipment</b>	<b>Voltage</b>	<b>Power</b>	<b>Current</b>	<b>Total Items</b>	<b>Amps</b>	<b>Total Items</b>	<b>Total Amps</b>	Class Size (Total Students)	
Item Name	Volts	Watts	Amps	per Group	per Group	per Class	per Class	Students Per Group	
								Total Groups	
								Circuit Rating (Amps)	
								Total Circuits	
								Total Circuit Capacity (Amps)	
							<b>Total Amps</b>	<b>Load Remaining</b>	

### Worksheet Terms and Formulas:

- **Module Name** – Name of maker module being assessed
- **Classroom Information**
  - *Class Size* – Total number of students in the class
  - *Students per Group* – Average number of students in each group
  - *Total Groups* – Total number of groups (Class Size / Total Groups)
  - *Circuit Rating (amps)* – Amp rating of an individual circuit
  - *Total Circuits* – Total number of circuits in the classroom
  - *Total Circuit Capacity (amps)* – Total available load in the classroom (Circuit Rating x Total Circuits)
- **Equipment**
  - *Item Name* – Name of tool/equipment required for the module
  - *Voltage (volts)* – Rated voltage of the tool
  - *Power (watts)* – Rated wattage of the tool (Volts x Amps)
  - *Current (amps)* - Rated amperage of the tool
  - *Total Items per Group* – Number of this tool needed per group

- *Amps per Group* – Total amperage requirement for this group for these tools (Total Items per Group x Amps)
- *Total Items per Class* – Total number of items needed for the entire class (Total Items per Group x Total Groups)
- *Total Amps per Class* – Total amperage requirement for the class for these tools (Total Items per Class x Amps)
- **Load Budget**
  - *Total Amps* – Total amps required for the entire module (Sum of all Total Amps per Class column)
  - *Load Remaining* – Total remaining capacity for the classroom (Total Circuit Capacity – Total Amps)

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